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Project Director: Dr. Steve H. Bomar, Jr.

Sponsor: Defense Nuclear Agency

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Project No: A-2149

Project Director: Dr. S. H. Bomar, Jr.

Sponsor: Defense Nuclear Agency

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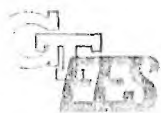
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ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

June 19, 1978

Commanding Officer
Defense Nuclear Agency
6801 Telegraph Road
Alexandria, Virginia 22310

Attention: Dr. George Ullrich

Subject: Monthly Technical Letter Report No. 1, "Techniques for Investigating Materials in a Radiant Heat Environment," covering the Period May 15 through June 14, 1978 (Georgia Tech Project A-2149).

Gentlemen:

The objectives of this program are:

- (1) To develop techniques for supplying concentrated solar radiant energy to a soil specimen lying in a horizontal plane in a manner which simulates the thermal pulse from a nuclear weapon,
- (2) To characterize the optical performance of the equipment developed in pursuit of the objective above, using scale models and a laboratory solar furnace,
- (3) To plan a series of tests to be conducted in collaboration with the Centre National de la Recherche Scientifique in France and to coordinate these plans with CNRS, the Defense Nuclear Agency, and other agencies and contractors as CNRS and DNA may direct.

During the first month, effort has been concentrated on investigation of optical concepts for turning and collimating the concentrated radiant beam and in making preparations for the use of a small solar furnace at Georgia Tech. Also, we have considered the use of thermistors having very small mass for measurement of the air column temperatures and the use of a laser system for measurement of the concentration of particulate material in the air column.

In the area of optical design, an existing computer program has been adapted to perform ray-tracing on candidate light pipe configurations. One light pipe surface has been generated on paper, in addition to the four conceived during the proposal preparation, and it was found that light arriving from directions near the horizontal axis will arrive at the sample with only one bounce.

Defense Nuclear Agency
June 19, 1978
Page 2

However, light arriving from wide angles will suffer many bounces before striking the sample. This work will be continued during the second month.

Another method for turning the incident beam has been suggested as shown in Figure 1. If a parabolic reflector were placed behind the focus of the solar furnace and a flat mirror were placed forward of the focus, it would be possible to turn the beam from a point-source sun as shown in the figure. Whether this scheme would work successfully with a sun of finite diameter is not yet clear; this question will be investigated by manual ray-tracing. The maximum time that the system would operate during one measurement is on the order of eight to ten seconds, and it should be possible for the optical apparatus to survive for this time if the concept is valid.

It was considered urgent that the small solar furnace be checked out and that two heat flux calorimeters be ordered early in the program so that these items would be ready when needed. The solar furnace required minor repairs to a gear drive mechanism and these have been accomplished. The calorimeters have been placed on order with a promised delivery date of two weeks after receipt of order.

We have had a telephone conversation with Dr. Mike McDonnell of Science Applications, Incorporated concerning coordination between the SAI and Georgia Tech efforts. SAI will send sketches of its latest light pipe design for our comments and we will consider modeling the design for our solar furnace tests. Also, it is expected that SAI personnel will visit the 400 kW Advanced Components Test Facility at Georgia Tech in the near future.

During the second month of the program, Georgia Tech effort will be concentrated on selection of two or more optical concepts for turning and collimating the optical beam. This selection must be completed so that construction of models can begin. Also, the thermistor idea for measuring air temperatures will be further developed. No difficulties which would impact the program budget or schedule are recognized at this time.

Respectfully submitted,

✓ Steve H. Bomar, Jr.
Project Director

jw

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Mr. Walton
Mr. Elfe

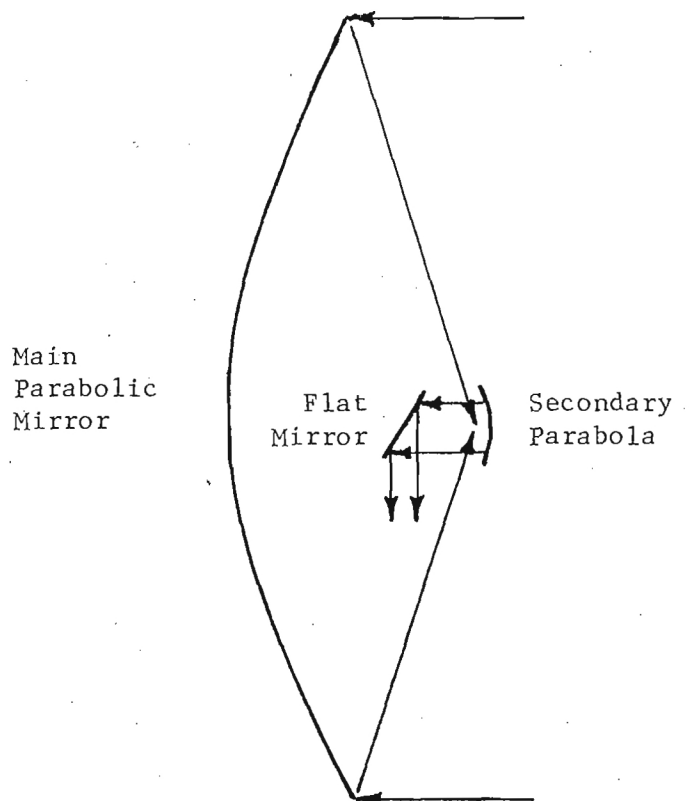


Figure 1. Concept for Turning Beam with Collimating Parabola and Flat Mirror.

A-2149



ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

July 24, 1978

Commanding Officer
Defense Nuclear Agency
6801 Telegraph Road
Alexandria, Virginia 22310

Attention: Dr. George Ullrich

Subject: Monthly Technical Letter Report No. 2, "Techniques for Investigating Materials in a Radiant Heat Environment", Contract DNA001-78-C0261, covering the Period June 15 through July 14, 1978 (Georgia Tech Project A-2149).

Gentlemen:

The objectives of this program are:

- (1) To develop techniques for supplying concentrated solar radiant energy to a soil specimen lying in a horizontal plane in a manner which simulates the thermal pulse from a nuclear weapon,
- (2) To characterize the optical performance of the equipment developed in pursuit of the objective above, using scale models and a laboratory solar furnace,
- (3) To plan a series of tests to be conducted in collaboration with the Centre National de la Recherche Scientifique in France and to coordinate these plans with CNRS, the Defense Nuclear Agency, and other agencies and contractors as CNRS and DNA may direct.

During the second month of the program, two specific light pipe designs have been inspected, the small solar furnace has been placed in operation, and the "double parabola" flux turning concept has been investigated further.

The ray-tracing computer program described in Monthly Technical Letter Report No. 1 has been used to investigate the number of ray bounces expected in the light pipe configuration shown in Figure 1. This resulted in 624 bounces for 177 rays, or about 3.5 bounces per ray. No rays returned through the aperture. The light pipe configurations shown in Figure 2 and 3 will be run next. The purpose of this activity is to select a light pipe geometry with the minimum number of bounces, and thus the minimum loss of flux, at the sample plane.

Commanding Officer
Attention: Dr. George Ullrich
July 24, 1978
Page 2

The small solar furnace to be used for model testing has been placed in operation and two Gardon calorimeters have arrived. The double parabola flux turning concept, described in Monthly Technical Letter Report No. 1, was investigated briefly on the solar furnace using a small parabolic secondary reflector salvaged from an automotive headlight. The results of this experiment were sufficiently encouraging to warrant further investigation and a parabolic mirror from a carbide lamp has been rigged for testing; this mirror is a good parabolic surface and has a wide aperture which should make it a good model for the intended purpose.

During the next reporting period, design of light pipe configurations will be accelerated and tests of the double parabola scheme will be continued. No difficulties which would impact the program budget or schedule are recognized at this time.

Respectfully submitted,

S. H. Bomar, Jr.
Project Director
Solar Energy and Materials
Technology Division

je

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A-2149
Mr. J. D. Walton
Mr. Tom Elfe

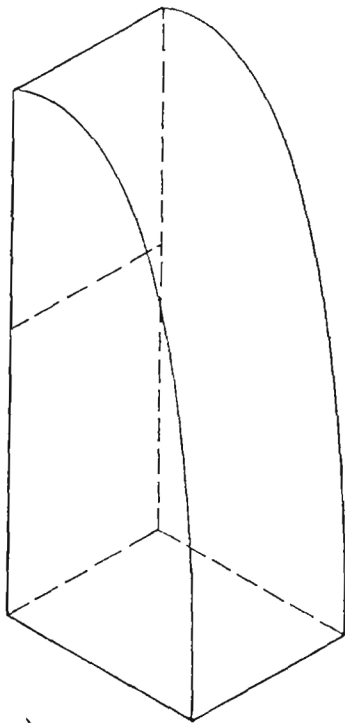


Figure 1. Light Pipe with Parabolic-Cylindrical Rear Wall and Flat sides

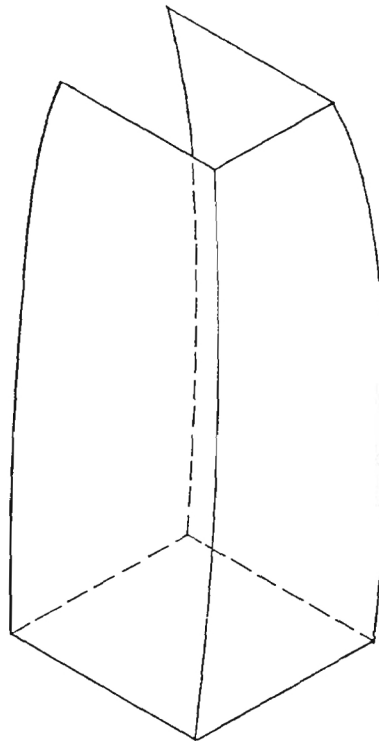


Figure 2. Light Pipe with Three Parabolic-Cylindrical Walls.

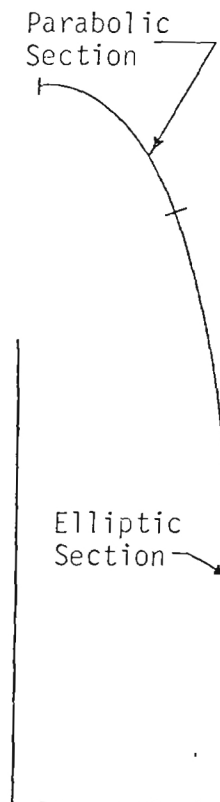


Figure 3. Two-dimensional sketch of Light Pipe with Parabolic and Elliptic Sections in Rear Wall.

A-2149

5/15/78 - 12/31/78

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TECHNIQUES FOR INVESTIGATING MATERIALS
IN A RADIANT HEAT ENVIRONMENT

Georgia Institute of Technology
Engineering Experiment Station
Atlanta, Georgia 30332

1 February 1979

Final Report

CONTRACT NO. DNA 001-78-C-0261

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Block 20, ABSTRACT (Continued)

solar furnace, and to plan a series of tests at the CNRS facility.

A variety of light pipe configurations and a multiple mirror design were considered for the proposed application. Models of two light pipes were built and tested; results indicate that one-third to two-thirds of the available flux level can be delivered to the soil specimen plane. It is recommended that small light pipe surface coupons be tested at CNRS in mid-1979 and that a prototype light pipe assembly be constructed and tested with soil samples in late 1979.

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SUMMARY

The long range objective of this program is to measure quantitatively the behavior of soil specimens while they are subjected to simulated thermal pulses from nuclear weapons. The CNRS 1000 kW Solar Furnace in France is capable of supplying the highest fluxes of concentrated solar radiation available at any facility in the world. The immediate purposes of this research program were to develop optical devices by which the soil measurements might be adapted to the CNRS facility, to perform scale model tests on these devices using a laboratory solar furnace, and to plan a series of tests at the CNRS facility.

A variety of light pipe configurations and a multiple mirror design were considered for the proposed application. Models of two light pipes were built and tested; results indicate that one-thirds to two-thirds of the available flux level can be delivered to the soil specimen plane. It is recommended that small light pipe surface coupons be tested at CNRS in the mid-1979 and that a prototype light pipe assembly be constructed for testing with soil samples in late 1979.

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SECTION I

INTRODUCTION

Prediction of the effects of nuclear weapons is a subject of considerable interest to the Defense Nuclear Agency. In order to perform these predictions by analytical methods, it is necessary that certain transport properties of the media surrounding the point of detonation be known; the transport properties of the atmosphere near the surface of the ground are of particular interest in this program. The overall objective of the present research effort was to develop techniques for measuring atmospheric properties near the ground surface during and shortly after the arrival of a simulated nuclear thermal pulse. Specifically, methods for obtaining high fluxes of radiant energy on a horizontal specimen were addressed.

DESCRIPTION OF THE PROBLEM

When a nuclear weapon is detonated in the atmosphere, energy is released by several mechanisms. Within the first 10^{-8} second or so, depending on yield, energy appears as kinetic energy of the materials of which the weapon was made, internal energy of these particles, and electromagnetic radiation of wavelengths ranging from the infrared region of the spectrum to x-rays (Ref. 1). Within less than one second, most of this energy is absorbed by the atmosphere within a few feet of the point of detonation and results in the creation of a spherical region containing air and weapon debris at temperatures of tens of millions of degrees and pressures of millions of atmospheres. This high-temperature, high-pressure region is known as the fireball, and it in turn releases energy as thermal radiation, a shock front propagated through the atmosphere, and as gamma radiation or high-energy x-rays. The fireball surrounding the point of detonation is effectively the source of the thermal radiation and shock phenomena.

The thermal radiation emitted from the surface of the fireball travels at the speed of light in all directions. The radiant energy arriving at the ground has roughly the wavelength distribution of sunlight arriving at the ground although the radiant intensity is many times greater than sunlight and diminishes in inverse proportion to the square of the distance to the fireball's surface. The radiant energy arrives at the ground almost immediately and appears as a pulse which rises very quickly and decays more slowly over a period of several seconds; the pulse duration is dependent on weapon yield. If the site of interest on the ground is sufficiently near ground zero and the weapon yield is sufficiently large, the thermal energy pulse can disturb the soil and the atmosphere immediately above the surface so that the transport properties of the atmosphere are altered. The air temperature may be increased and water vapor and particulate materials may be ejected into the air.

The rapidly expanding high-pressure gases within the fireball couple to the surrounding atmosphere and generate a radially expanding shock wave which travels initially at many times the speed of sound in air but much slower than the speed of light. The propagation of the shock wave in the air is affected by the local Mach number ahead of the shock front, the heat capacity of the air, and the pressures ahead of and behind the shock front; the local Mach number is governed by the heat capacity, density and temperature of the air (Ref. 2). Thus, the heat

capacity, density, pressure and temperature ahead of the advancing shock front are the transport properties governing the movement of the front. If these properties have been altered by the action of the thermal pulse before the shock front arrives, then the behavior of the shock will be altered in comparison to its behavior in undisturbed air.

The phenomenon known as the "Mach Effect" illustrates the importance of shock wave modification (Ref. 1), paragraphs 2.33-2.35-3.20-3.25). The incident (or initial) shock propagates radially from the point of detonation until it contacts the ground directly beneath the fireball. After the incident shock contacts the ground, it continues to move through the atmosphere and a reflected shock wave develops behind the incident wave. The speed of the reflected wave, however, is greater than the speed of the incident wave because it is traveling through air which has been disturbed by the passage of the incident wave. The reflected shock wave soon catches the incident wave and they form a merged shock wave known as a "Mach Stem." The Mach Stem moves through undisturbed air; it is characterized by an overpressure (pressure behind the wavefront) on the order of twice the overpressure of the initial wave alone (Ref. 1, paragraph 3.18). Thus the modification of the propagation medium (air) by the initial shock has resulted in development of a merged shock wave which has about twice the overpressure of the initial wave. The potential for blast damage to targets on the ground is correspondingly increased. It is clear that alteration of the transport properties of the atmosphere can cause significant perturbations in nuclear weapons effects.

When the thermal radiation from a nuclear explosion impinges on a heat-absorbing surface, such as desert, coral, or asphalt, a hot layer of air, known as a "thermal layer" is produced (Ref. 1, paragraph 3.72-3.73). The thermal layer often includes smoke, dust, and other particulate matter. It forms before the arrival of the shock wave from an air burst, and interaction of the wave with the heated layer may affect the reflection process to a considerable extent. Under certain conditions, an auxiliary shock wave, known as a "precursor," can form and move ahead of the main incident wave. Severe modification of the usual blast wave characteristics may occur within the precursor region. Precursor formation is not to be expected over non-dusty and heat-reflecting surfaces, such as concrete, snow, ice, or water.

The problem of interest in the present work is the measurement of the changes in atmospheric properties above a soil surface exposed to a simulated nuclear thermal pulse. The data sought are the transport properties of the atmosphere (temperature, density, concentration and description of materials ejected from the specimen surface) and documentation of the behavior of the system during exposure to high radiant heat fluxes. To accomplish this, one must devise suitable means for exposing the sample to radiant energy at sufficiently high flux levels.

DEFINITION OF TEST REQUIREMENTS

Since the wavelength distribution of thermal radiation from a nuclear explosion fireball is roughly similar to the wavelength distribution of sunlight at the earth's surface, concentrated solar radiation is suitable for simulating nuclear thermal pulses. The problem is to achieve sufficiently high incident fluxes of sunlight to adequately simulate the peak fluxes of the fireball's thermal pulse. For many years, large solar furnaces have been used for

measurements of this type; two of the world's major solar test facilities were constructed primarily for this purpose: the U. S. Army Solar Furnace at White Sands, New Mexico, and the French Army Laboratoire Central de l'Armement at Odeillo, France. These two solar furnaces collect on the order of 25 to 50 kW of thermal power.

The desired measurements may be conducted by exposing specimens of soil to pulses of concentrated solar radiation generated by solar furnaces. Science Applications, Incorporated has conducted tests of this type on soil specimens for the Defense Nuclear Agency at the U. S. Army White Sands Solar Furnace in New Mexico (Ref. 3). These studies are generally known as "soil blowoff phenomena" measurements and involve determination of such parameters as soil and air temperature, type and quantity of materials ejected from the specimen, blowoff velocities, etc., while the specimens are irradiated in the solar furnace. At White Sands, incident radiant fluxes up to about 60 cal/cm²s were achieved. Smoke was emitted from nearly all soil types at fluences above a threshold of about 5 cal/cm² (fluence = flux x time), small particles were emitted from most soil types at fluences in the range of 5 to 25 cal/cm², jets or flakes were explosively emitted from soils containing abundant clays at fluences in the range of 25 to 50 cal/cm², and steam was emitted from all moist soils. The fluxes available at the White Sands Solar Furnace, however, were not sufficiently high to adequately cover the range of experimental interest.

The size and optical configuration of the CNRS 1000 kW Solar Furnace at Odeillo, France are substantially different from those at White Sands. The thermal power available at the focal zone is about 40 times as large (1,000 kW versus 26 kW) and the peak heat flux is about four times as large (1,600 W/cm² versus 360 W/cm²). Thus, it should be possible to conduct tests over a much wider range of incident fluxes and fluences at the CNRS facility than at the White Sands facility, if certain experimental requirements can be met. These requirements, defined by the Defense Nuclear Agency and its contractors concerned with the soil blowoff phenomena problem, are:

- (1) The soil sample should lie in a horizontal plane with the incident radiation arriving downward from a direction approximately normal to the sample plane.
- (2) The atmosphere above the soil should be surrounded by a column with reflecting walls so that the atmosphere appears to be an infinite medium; the height of the column should be two to four meters.
- (3) The linear dimension(s) of the sample should be 15 to 30 cm (6 to 12 inches); a round or square sample configuration is preferred.
- (4) The transport properties of the atmosphere must be determined as functions of time and height above the sample plane, beginning at the time of initiation of the thermal pulse and ending at the time of shock wave arrival for the weapon parameters under consideration.
- (5) The soil behavior must be documented photographically and particle samples should be collected at various heights above the specimen plane.

- (6) The optical system used to turn or otherwise process the beam of concentrated solar radiation arriving at the focal zone of the solar furnace must cause a minimum attenuation of the incident flux.

The Defense Nuclear Agency has defined the following experimental conditions as the range of interest for soil blowoff phenomena experiments:

- (1) Weapon yields: 1 kT and 1 MT (kT - 1 kiloton of TNT)
- (2) Scaled ranges: $185 \text{ ft/kT}^{1/3}$ to $600 \text{ ft/kT}^{1/3}$
- (3) Heights of burst: about $50 \text{ ft/kT}^{1/3}$ to $600 \text{ ft/kT}^{1/3}$

These scaled ranged and heights of burst are represented by the rectangular shaded area shown in Figure 1. It is necessary to determine whether a significant portion of this experimental range can be simulated at the CNRS 1000 kW Solar Furnace.

Such an estimate can be made if one assumes that certain power levels are available at the CNRS facility, then estimates the incident fluxes which might be expected on the ground using data in Reference 1. A sample calculation for one data point is given for illustration:

- (1) Assume that the average power level over a 15 cm (6 inch) diameter circular area at the focus of the solar furnace is $294 \text{ cal/cm}^2\text{s}$ (Ref. 4).
- (2) The geometry of the system is shown in Figure 2. If there is no atmospheric attenuation, the thermal power may be regarded as spread uniformly over the surface of a sphere of area $4\pi R^2$, where R = the distance from the explosion (Ref. 1, paragraph 7.99).
- (3) The maximum rate of thermal emission from the fireball is given by $P_{\text{max}} = 4 W^{1/2} \text{ kT/s}$, where W = the weapon yield in kT (Ref. 1, paragraph 7.92) and the explosion of a 1 kT weapon releases 10^{12} calories (Ref. 1, Table 1.41).
- (4) The maximum flux arriving at the target is given by:

$$F_{\text{max}} = \frac{(P_{\text{max}})(\cos \phi)}{A_{\text{sphere}}}$$

Where the angle ϕ is defined in Figure 4. Also,

$$\cos \phi = \frac{\text{height of burst}}{\text{range}}$$

- (5) The two equations above may be combined to relate the range and height of burst which can be simulated with the assumed maximum flux:

$$\text{height of burst} = (\text{range})(\cos \phi) = \frac{4\pi (\text{range})^3 F_{\text{max}}}{P_{\text{max}}}$$

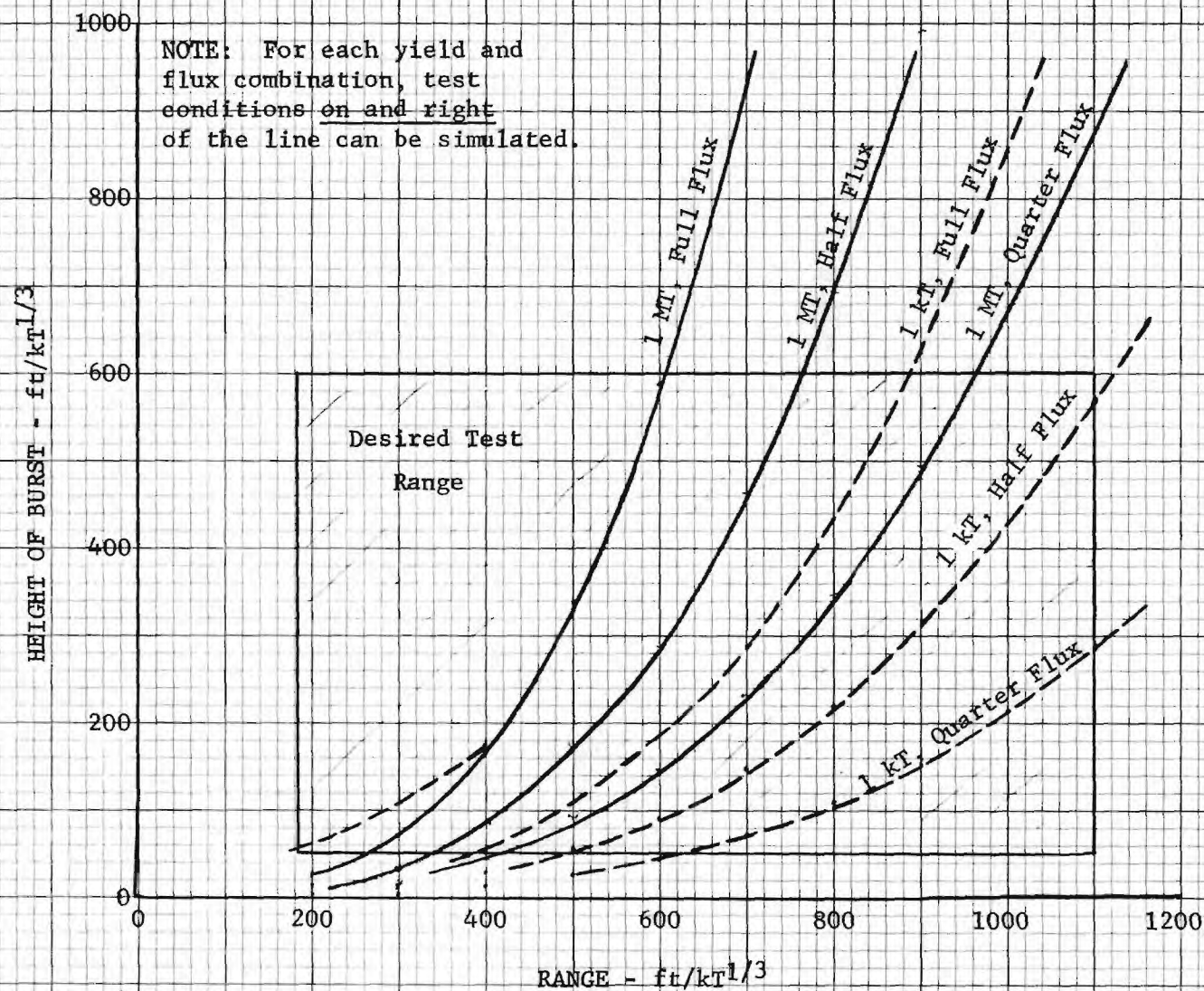


Figure 1. Scaled ranges and heights of burst for measurement of soil blowoff phenomena.

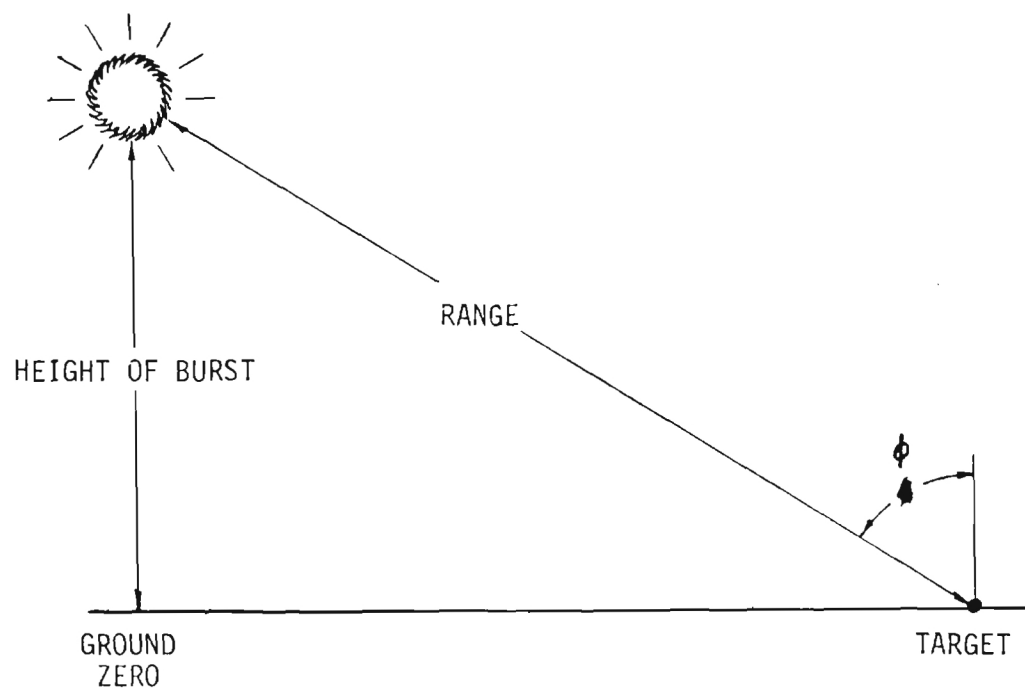


Figure 2. Geometry for calculation of peak heat flux at target on ground.

$$= \frac{4\pi (30.48 \text{ cm/ft})^2 (\text{range ft})^3 (294 \text{ cal/cm}^2\text{s})}{(P_{\text{max}} \text{ kT/s})(10^{12} \text{ cal/kT})}$$

where the height of burst and range are expressed in feet and P_{max} is expressed in kT/s.

- (6) For a sample data point, set $W = 1$ kT and the range = 800 feet. Then $P_{\text{max}} = 4$ kT/s and the height of burst = 439 feet.

The curves in Figure 1 overlaying the shaded area were constructed using the procedure described above. The curves represent weapon yields of 1 kT and 1 MT with maximum incident fluxes corresponding to the average available over a 15 cm (6 inch) diameter circle at the focal plane of the CNRS 1000 kW Solar Furnace (294 cal/cm²s), one-half this average flux, and one-quarter this average flux. If the specified incident fluxes can be attained on the specimen surface, the desired thermal pulse simulation can be performed for combinations of weapon range and height of burst lying on and to the right of the respective curves. Figure 1 shows that the 1 kT yield is the more difficult to simulate and that loss of flux caused by beam-turning devices will severely limit the range of desired test conditions which can be observed.

For high-yield bursts and short ranges, the shock wave will arrive at the target before the thermal pulse reaches its maximum intensity. This fact limits the maximum intensity required to simulate such cases and slightly increases the portion of the shaded area in Figure 1 which can be simulated at the CNRS Solar Furnace. This small effect operates only at the lower end of the 1 MT curves, and is shown by a dashed line for the 1 MT, Full Flux case.

CHARACTERISTICS OF THE CNRS 1000 KW SOLAR FURNACE

The CNRS Solar Furnace can attain, by far, the highest heat fluxes of any solar test facility in the world. Since achieving the highest possible fluxes is seen to be the overwhelming need for further soil blowoff phenomena tests, this facility is clearly preferred for further testing. The most formidable technical problem to be solved is the turning and collimation of the radiation beam incident on the focal plane. The solar furnace, illustrated schematically in Figure 3, employs 63 flat mirrors (heliostats) which track the sun and redirect a uniform beam of radiant energy onto the fixed parabola. The parabola, which is supported on the north side of a laboratory building, concentrates the radiant energy to a focal point. The focal point is positioned in a smaller building between the heliostats and the concentrating paraboloid dish. It is clearly seen in Figure 3 that the optical axis of the system is horizontal; since it is desired that radiation arrive on the soil specimen from a vertical direction, it is necessary to turn the incident beam through an angle approaching 90 degrees.

Another feature which is evident in Figure 3 is the convergence of the incident beam at the focal point. This is illustrated more specifically in Figure 4 which shows the geometry of the focal point with respect to the paraboloid concentrator. This wide-aperture characteristic of the CNRS Solar Furnace is in large measure responsible for the very high incident fluxes available there. The maximum flux available in an optical system increases as the diameter to focal length ratio increases; this ratio at the CNRS facility was chosen to give fluxes

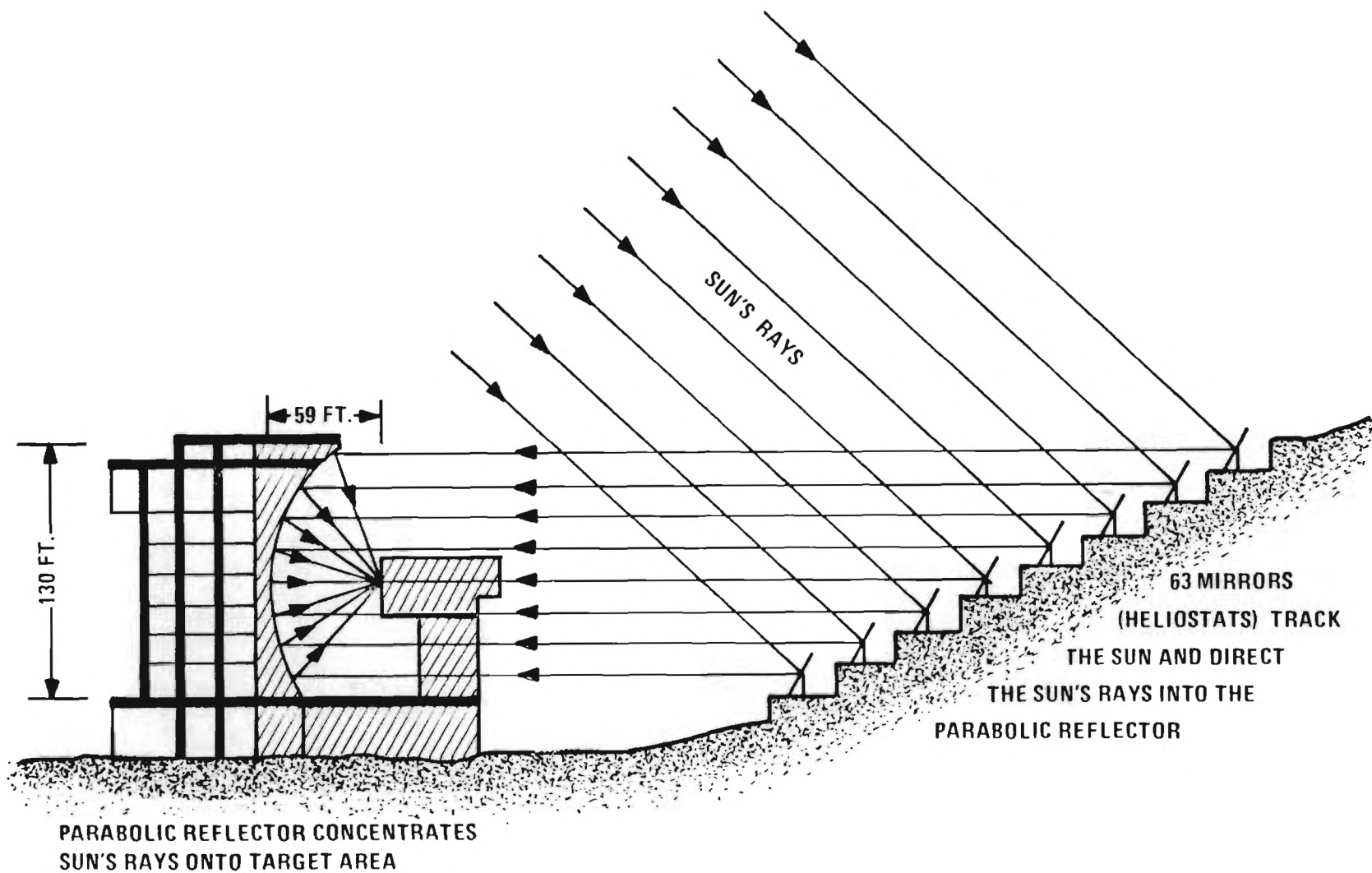


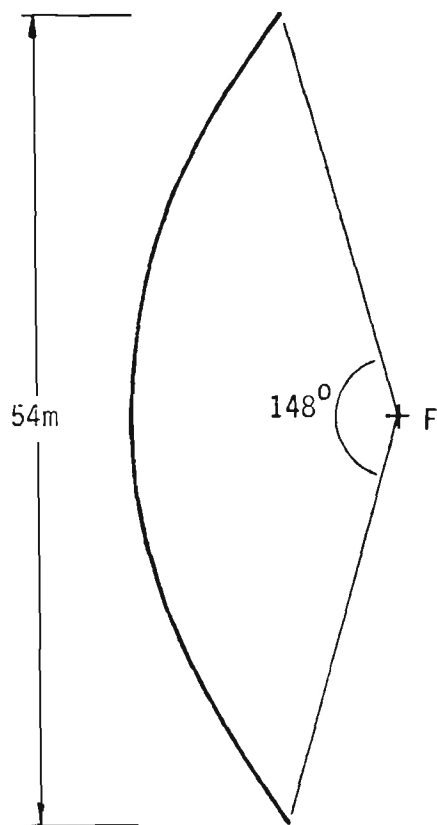
Figure 3. Schematic diagram illustrating operation of the CNRS Solar Furnace.

near the maximum theoretical values on a plane passing through the focus and perpendicular to the optical axis (Ref. 5). (A camera lens is an analogous optical device in which the light gathering power is proportional to the area to focal length ratio.) Since wide angle radiation represents an important fraction of the energy arriving at the focal plane, any optical device used to turn and collimate the beam must adequately recover this radiation component.

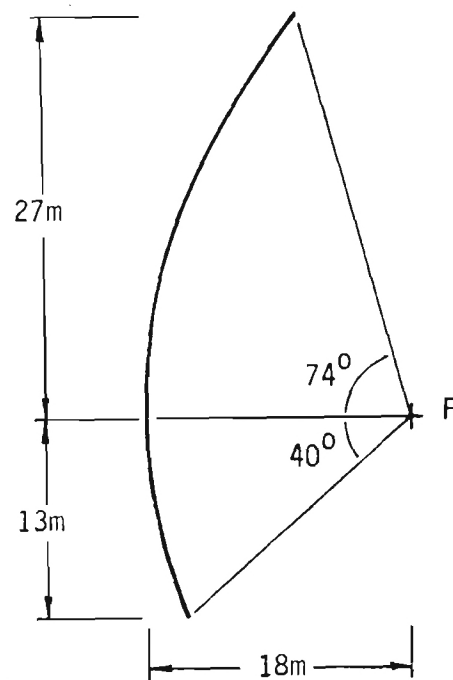
Figure 5 shows an incident flux map for the CNRS Solar Furnace. The map is on a plane passing through the focus and tilted back 25 degrees from the vertical; this tilt angle compensates somewhat for the truncation of the bottom of the parabolic concentrator and gives the most uniformly round flux contours. A tilted focal plane is advantageous in the present case because the beam need not be turned a full 90 degrees to achieve a vertically downward direction. The square aperture drawn in Figure 5 illustrates the approximate specimen size desired for soil blowoff tests.

Figures 6 and 7 show the CNRS focal building as viewed from the west. The scale drawing in Figure 7 illustrates the position of the focal point and a conceptual representation of a light pipe and specimen. The two floor levels available for setting up experiments would permit a vertical column length up to about four meters (14 feet), although optical loss considerations make it unlikely that such a long column would be used.

Figures 8 and 9 illustrate the focal room at the CNRS Solar Furnace as seen from the paraboloid concentrator. (These photographs were made in September 1978.) In Figure 8, the sample to be irradiated is the small, hexagonal radar array at the center of the picture. It is surrounded by a water-cooled aluminum shield which masks the unwanted radiant energy around the sample. Two water-cooled, moveable panels which serve as shutters are on either side of the sample; these open in about 0.1 second and close in about 0.3 second under electronic control. The structure in front of the sample, covered with aluminum foil, is a microwave receiving antenna and supporting boom. In Figure 9, the moveable shutters are closed and the solar furnace is in operation; the area in the vicinity of the focal point is thus very brightly illuminated. As seen in Figures 6 through 9, the physical arrangement of the CNRS Solar Furnace provides for great flexibility in the design and testing of experimental hardware.



HORIZONTAL SECTION
AT FOCAL PLANE



VERTICAL SECTION
AT FOCAL PLANE

(The parabola is truncated at the bottom to lower the focal point toward ground level.)

4
Figure 4. Geometry of Focal Point with Respect to Parabola at CNRS Solar Furnace.

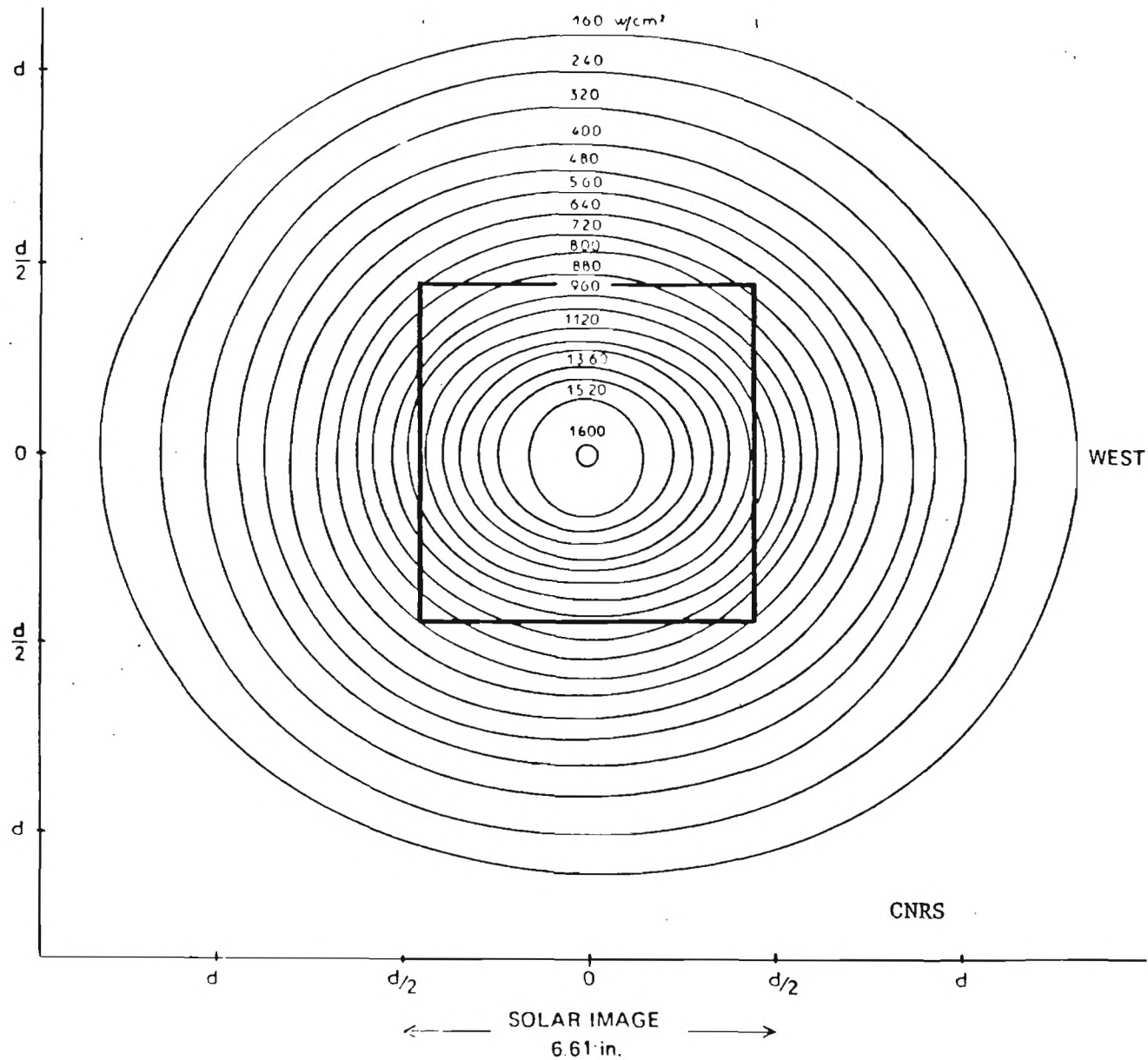


Figure 5. Incident flux map for CNRS 1000 kW Solar Furnace (a 15 cm (6 inch) square aperture is shown at the center).

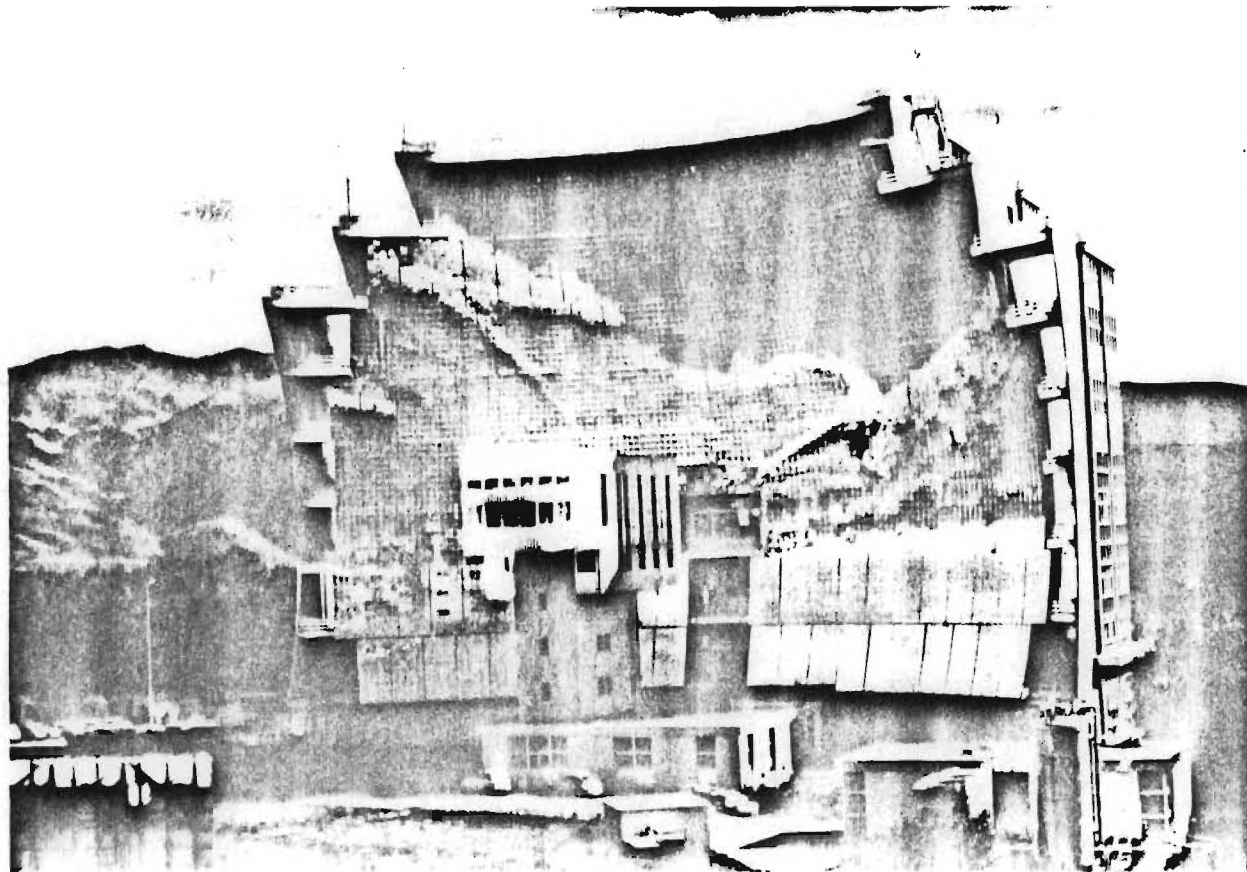


Figure 6. Parabolic concentrator and focal building at CNRS 1000 kW Solar Furnace.

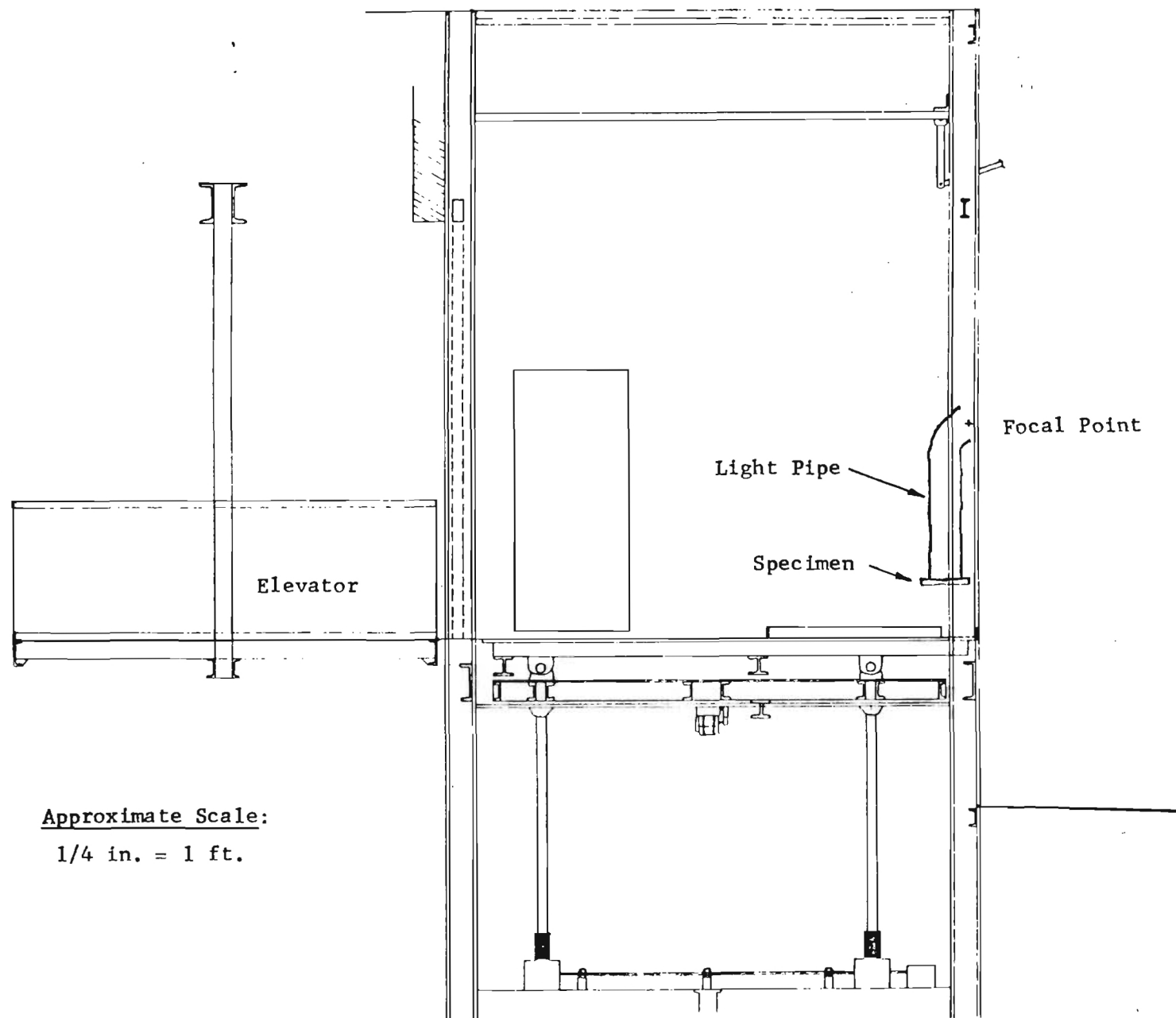


Figure 7. West side elevation of focal building at CNRS Solar Furnace.

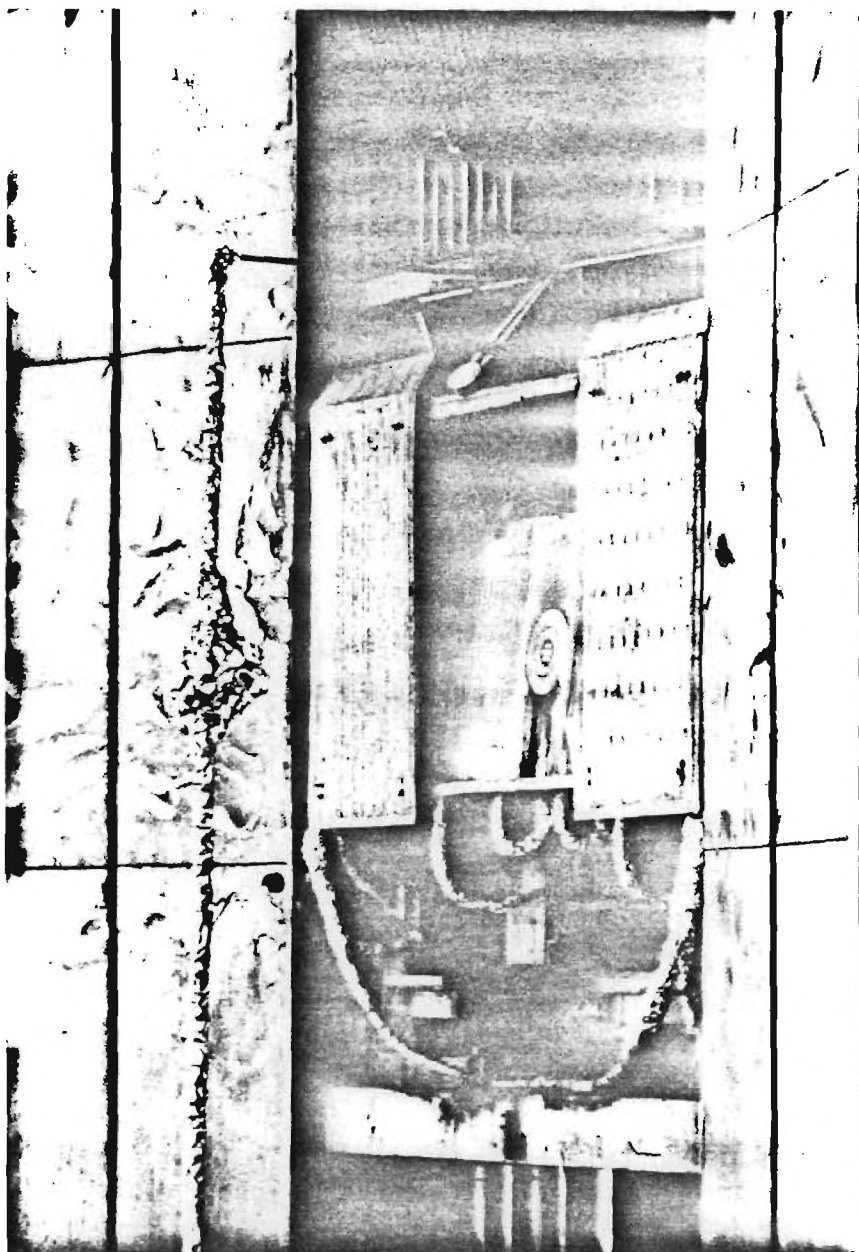


Figure 8. Specimen, water-cooled shields and shutters in focal room at CNRS Solar Furnace.

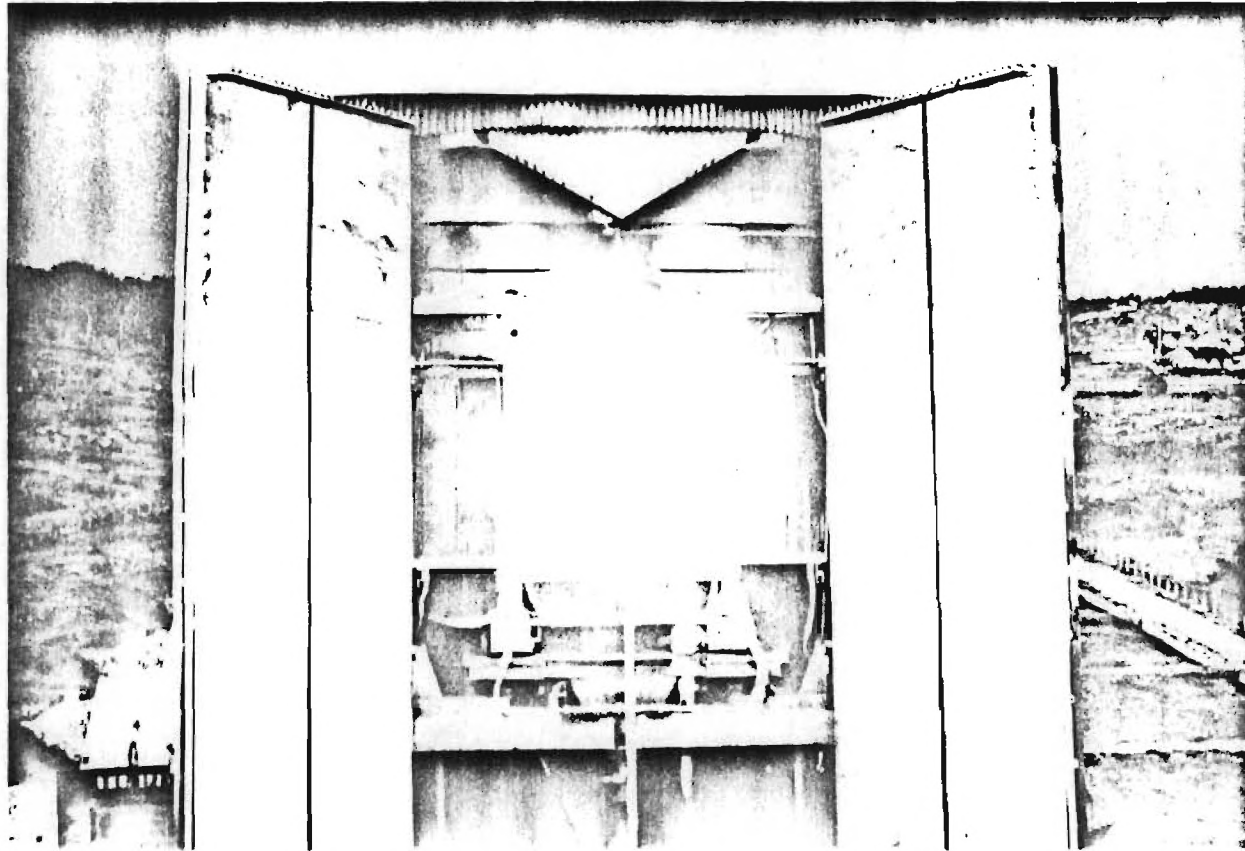


Figure 9. Focal room at CNRS Solar Furnace with shutters closed.

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SECTION II

EXPERIMENTAL WORK

CONTRACT OBJECTIVES

This contract was intended to explore the feasibility of turning and collimating the concentrated beam of solar radiation available at the CNRS 1000 kW Solar Furnace, in order to perform measurements of soil blowoff phenomena. Since it was not clear that such operations on the beam could be done without suffering prohibitive flux losses, this program was designed to apply a limited amount of effort and funds to the problem before committing major resources for a full-scale test program. The research contract was a combination design and experimental testing effort with the following defined objectives:

- (1) To develop techniques for supplying concentrated solar radiant energy to a soil specimen lying in a horizontal plane in a manner which simulates the thermal pulse from a nuclear weapon,
- (2) To characterize the optical performance of the equipment developed in pursuit of the objective above, using scale models and a laboratory solar furnace,
- (3) To plan a series of tests to be conducted in collaboration with the Centre National de la Recherche Scientifique in France and to coordinate these plans with CNRS, the Defense Nuclear Agency, and other agencies and contractors as CNRS and DNA may suggest.

LABORATORY-SCALE SOLAR FURNACE

A small solar furnace on the campus of the Georgia Institute of Technology was used for evaluation of scale model optical hardware developed on this program. This solar furnace is shown in Figure 10 and consists of a tracking heliostat and a paraboloid dish concentrating reflector. The geometric details of the concentrating dish, a military surplus searchlight reflector, are shown in Figure 11. Comparison of Figure 4 and Figure 11 shows that the CNRS and laboratory solar furnaces have rim angles of 74 and 62 degrees, respectively. At the CNRS Solar Furnace, 50 percent of the energy at the focal plane is delivered within a circle about 28 cm in diameter (1.6 solar image diameters) (Ref. 4); it is estimated that the laboratory-scale solar furnace delivers 50 percent of its energy within a circle about 2.5 cm in diameter (about 4 solar image diameters). Making the rather gross assumptions that the reflectivities of the heliostats and concentrators are similar, that the insolation values and cosine losses are similar, etc., the maximum fluxes available on the two facilities should be related by the relative areas over which the images are spread:

$$\begin{aligned}\frac{Q}{A} \text{ lab} &= \frac{Q}{A} \text{ CNRS} \left[\frac{\text{number of image diameters for CNRS}}{\text{number of image diameters for lab}} \right]^2 \\ &= 1,600 \text{ W/cm}^2 \left[\frac{1.6}{4.0} \right]^2 = 256 \text{ W/cm}^2\end{aligned}$$

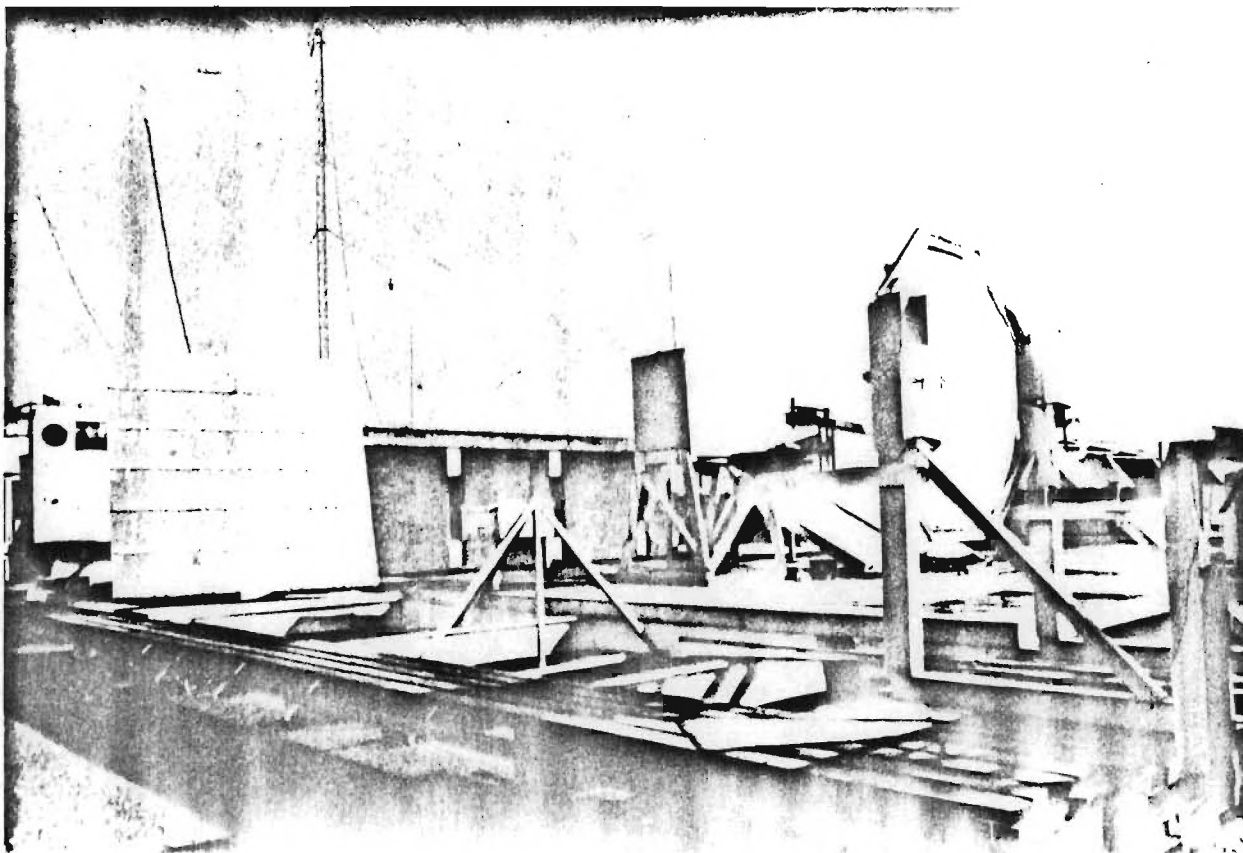
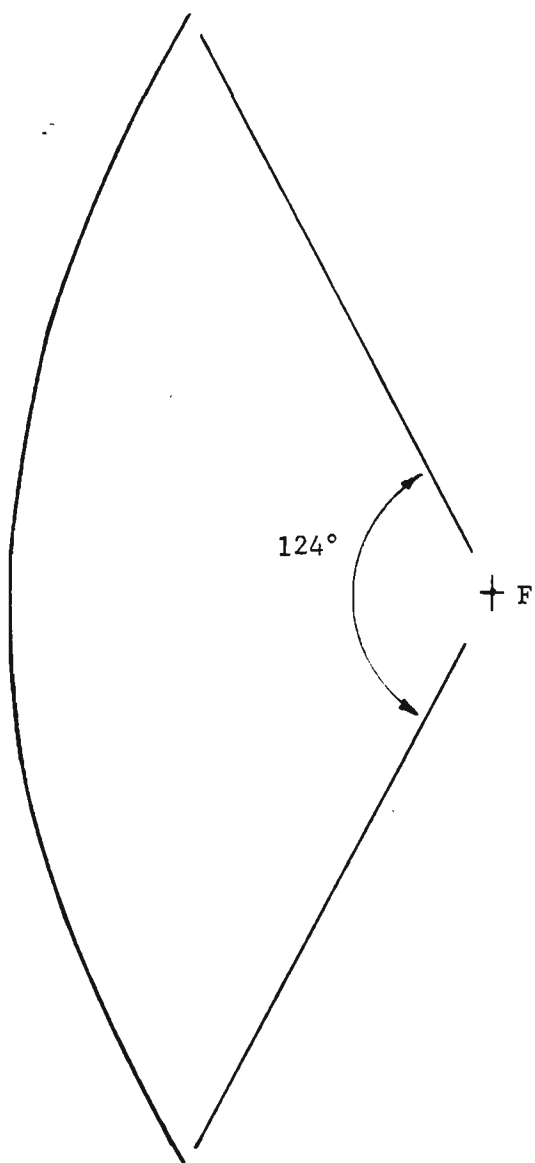


Figure 10. Photograph of laboratory-scale solar furnace on Georgia Tech campus.



Diameter = 152 cm (60 in.)

Focal Length = 63.5 cm (25 in.)

Theoretical Solar Image Diameter =
 $2 f \tan 16' = 0.59 \text{ cm (0.23 in.)}$

Thermal Power at Focal Point =
 approximately 1.3 kW

Figure 11. Configuration of paraboloid dish concentrator on laboratory-scale solar furnace.

This value is, in fact, approximately the maximum flux measured on the laboratory solar furnace.

The laboratory solar furnace was judged to be adequate for evaluation of scale model hardware on this program for these reasons:

- (1) Its rim angle is reasonably close to the rim angle at CNRS.
- (2) Its maximum flux is in the same order of magnitude as CNRS.
- (3) It is readily available and inexpensive to use for scale model tests.

Heat flux measurements were made using Gardon-type calorimeters (Ref. 6). These were water-cooled so that they could survive prolonged exposure at the focus of the solar furnace. The calorimeters were purchased from Hy-Cal Engineering of Santa Fe Springs, California and calibrations were furnished by the manufacturer. A photograph of one calorimeter is shown in Figure 12; the active area is 3 mm in diameter.

DOUBLE REFLECTOR FLUX TURNING DEVICE

The overall experimental objective of this program was to devise a method for turning and collimating a beam of concentrated solar radiation. The original beam is strongly converging and arrives along a horizontal axis. It is obvious that the radiant energy should experience the smallest possible number of reflections in order to minimize losses of flux intensity. One concept which appeared attractive was the double reflector scheme, shown schematically in Figure 13, because any given beam should be reflected from only two surfaces. A small secondary parabola is positioned so that its axis and focus coincide with those of the main parabola. A collimated beam will then emerge from the secondary parabola, as shown in Figure 13, and the high-flux collimated beam can be turned to the required final direction by a flat mirror. Two conditions must be met for these relationships to hold exactly:

- (1) The sun must be a point source of light.
- (2) The mirrors must have theoretically perfect shapes and dimensions.

The question to be addressed in investigating this concept was whether the above conditions could be closely enough approximated in practice to yield output fluxes suitable for soil blowoff tests.

The apparatus shown in Figure 14 was constructed to test the double reflecting device concept. The position of the secondary parabola was adjustable with respect to the flat mirror. The collimating tubes visible in Figure 14 were not initially used. Early trials with small paraboloid mirrors revealed that the finite diameter of the solar image from the main parabola caused beam spreading which might be corrected by adopting a spheroid shape for the small mirror. This modification gave promising results when very short working distances were used between the small curved mirror and the flat mirror, but at the expense of substantial shading of the small curved mirror by the flat mirror. The collimating tubes shown in Figure 14, which were Pyrex tubes coated internally with aluminum reflecting films, were added to reduce beam spread and permit longer working distances. Losses in the collimating tubes, however, reduced the output flux to levels which were no longer useful.

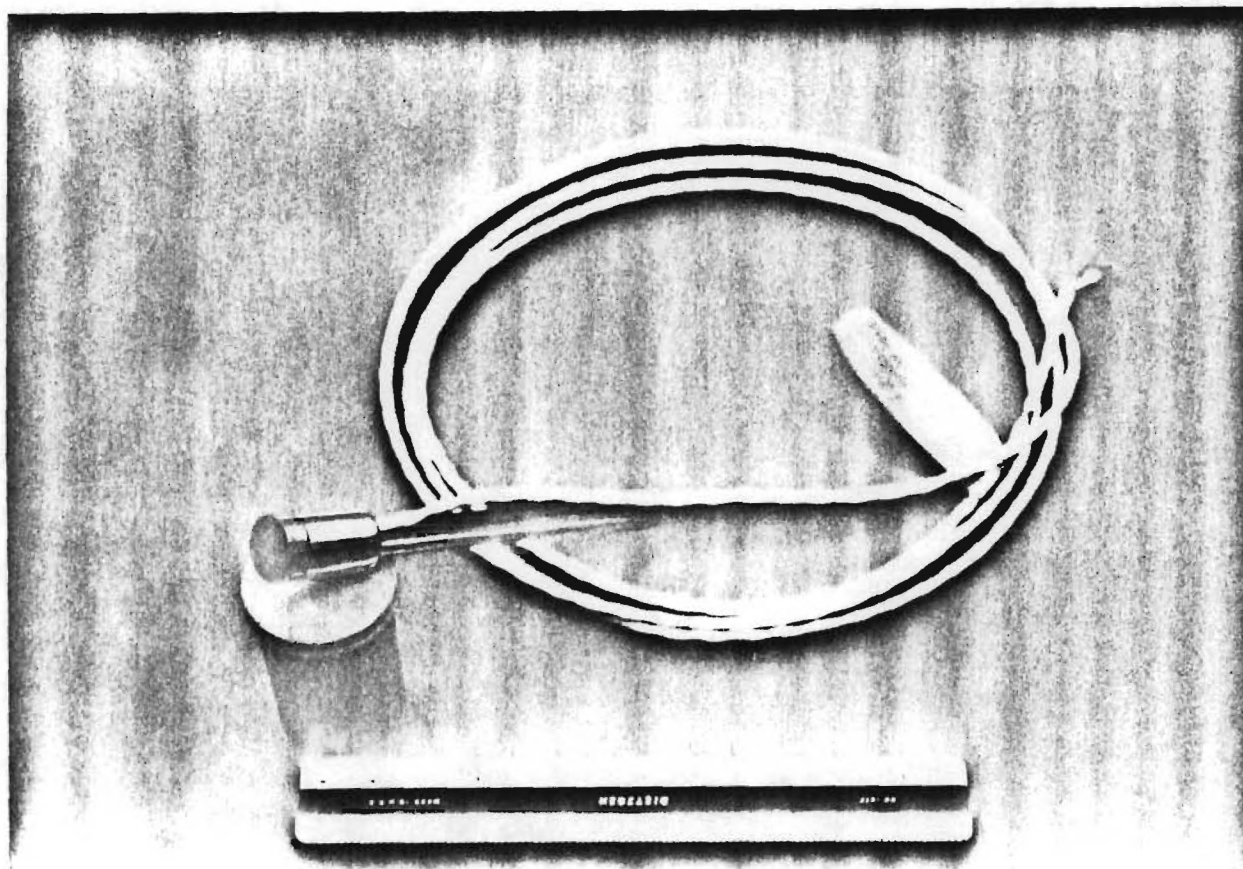


Figure 12. Water-cooled Gardon-type calorimeter manufactured by Hy-Cal Engineering, Santa Fe Springs, California.

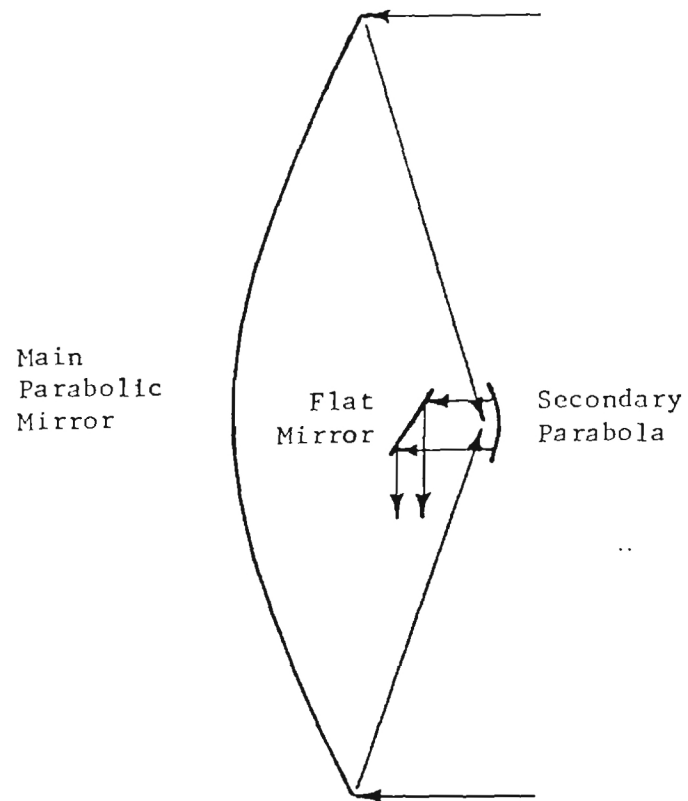


Figure 13. Schematic diagram showing double reflector flux turning concept.

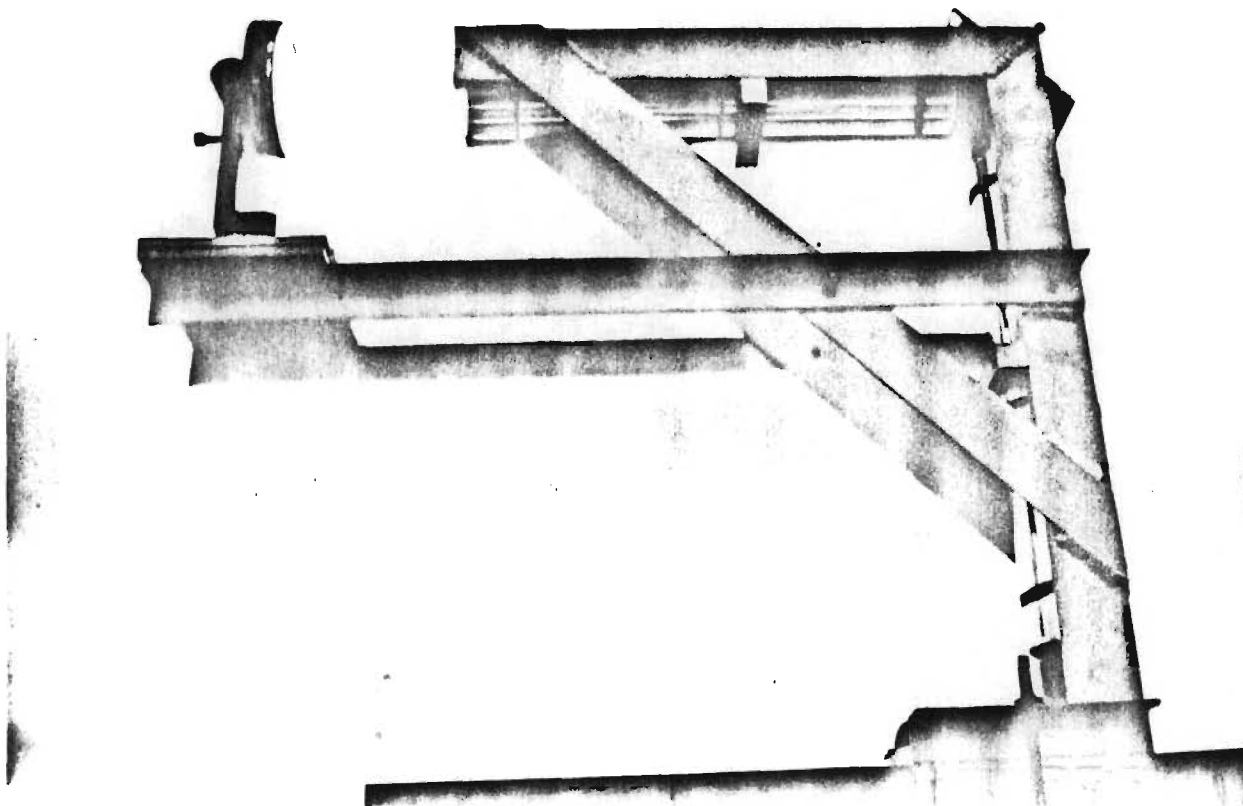


Figure 14. Double reflector flux turning device test apparatus.

The double reflector flux turning device was finally abandoned as a candidate concept for the following reasons:

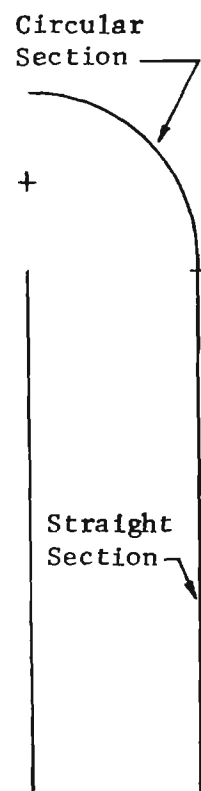
- (1) The theoretical solar image diameter of the main parabola represents an area receiving approximately the desired level of energy flux. The final output beam must be about this diameter, and certainly not more than a factor of two larger, if useable output fluxes are to be obtained.
- (2) If the output beam is to be similar in size to the main parabola's theoretical solar image size, then the small parabolic mirror must have an active area approximating these same dimensions. The finite-diameter solar image will thus be spread over most of the surface of the small curved mirror, resulting in poor collimation of its output beam.
- (3) The poorly collimated beam from the small curved mirror can be corrected by (a) very short working distances at the expense of shadowing, or (b) collimating tubes at the expense of prohibitively high reflection losses. Neither of these approaches yields useable output fluxes.

LIGHT PIPE DESIGNS

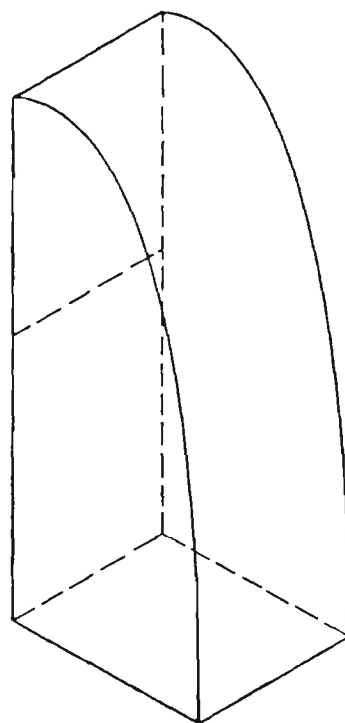
Preliminary consideration of optical hardware suitable for turning the flux at the CNRS Solar Furnace and providing the enclosed column for the atmosphere above the specimen led to the conclusion that hollow light pipes with internally reflecting walls should receive primary consideration. It is desirable that the light pipe configuration allow for disassembly, so that the walls might be cleaned and polished, and that the column above the soil specimen be square or circular in cross section, so that analytical modeling will be facilitated.

Approximately ten light pipe configurations were inspected by manual ray tracing techniques to identify promising candidates for further analysis. Four of these are described in Figure 15 and Table 1. As these designs evolved, all using approximately square cross sections, it became clear that utilization of the radiant energy arriving from wide angles near the horizontal direction would be improved by adopting a semi-circular cross section for the light pipe (Note the angles shown in Figure 4).

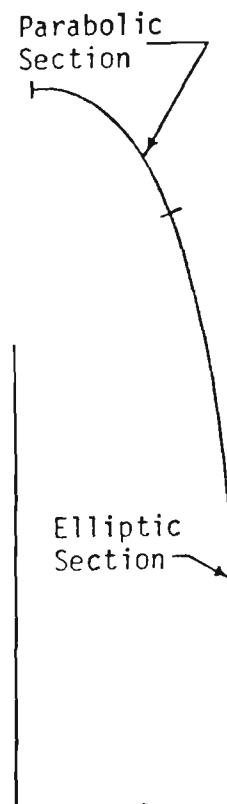
The optical configuration shown in Figure 16 was selected to serve as a basic light redirecting structure. This device is composed of three concentric conic sections which receive radiation through an aperture and turn it generally in a downward position. If the solar image at the aperture were a point, rather than having a finite diameter, one could design a curved surface dome for this flux turner from which each reflected ray emerged in the desired direction. The sun's finite diameter, however, prohibits this in the real case. Since a reflector consisting of multiple conic sections is much easier to construct than a continuously curved dome, especially in large sizes, the conic geometry was adopted as being substantially as good as a dome in the real case. The dimensions of the conic sections were selected by manual trials to reflect a large fraction of the rays downward toward the specimen. The aperture diameter was chosen to be about two solar image diameters, which at CNRS would capture about 60 percent of the incident power.



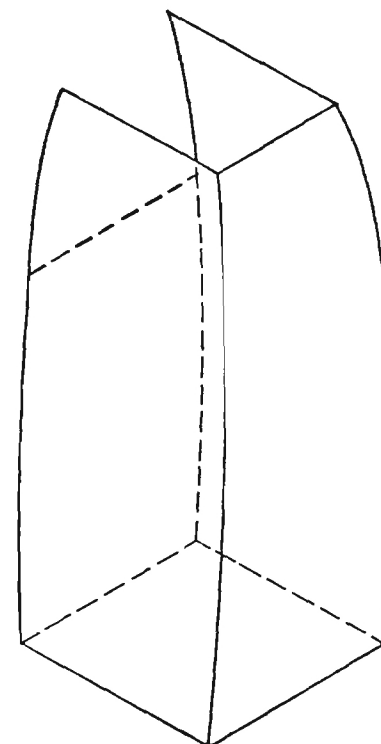
(a)



(b)



(c)



(d)

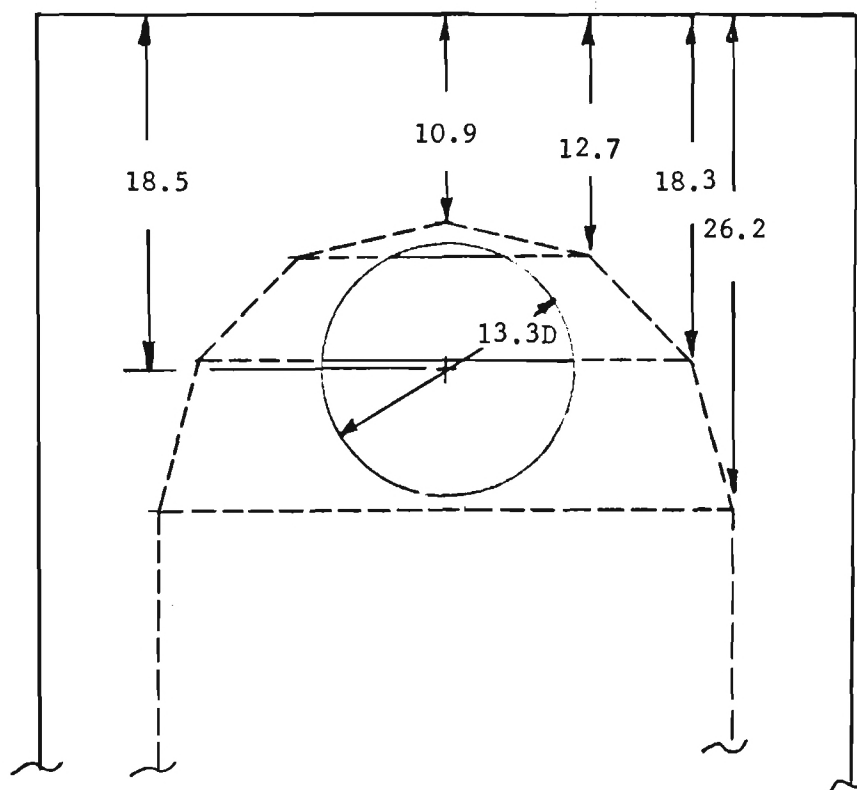
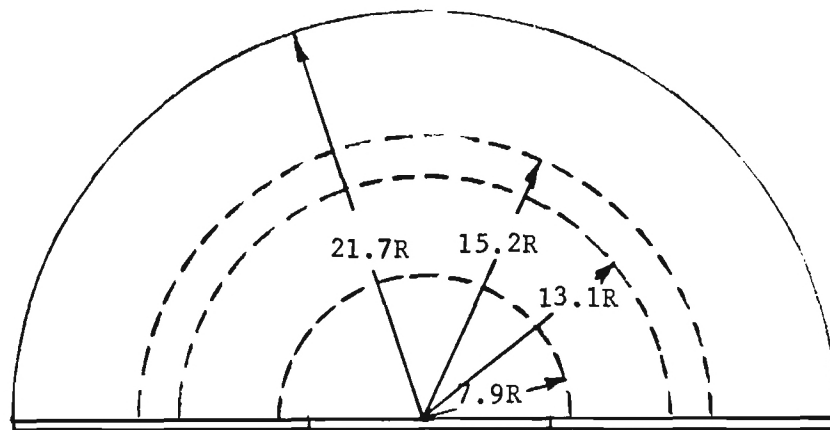
Figure 15. Four candidate light pipe configurations for soil blowoff tests.

Table 1. Data for candidate light pipes.

Sketch Shown in Figure 15	Description	Remarks
(a)	Cylindrical-straight rear wall and flat sides (two-dimensional sketch)	Large fraction of entering light is reflected back through aperture
(b)	Parabolic-cylindrical rear wall and flat sides (three-dimensional sketch)	Average 3.5 bounces per ray for point-source sun; sample plane too large
(c)	Parabolic-elliptic rear wall and flat sides (two-dimensional sketch)	Hot spot on sample plane
(d)	Three parabolic cylindrical walls and open top (three-dimensional sketch)	Very difficult to construct.

Below the domed light-turning structure, a column was constructed to funnel radiation onto the specimen and to confine the atmosphere above the specimen. Two models of this light pipe configuration were built for testing in the laboratory solar furnace. The models were scaled to the furnace's solar image diameter of 0.59 cm (0.23 in.); they are shown in Figures 17 and 18. One has a straight cylindrical pipe section downstream of the domed structure and the other has a cone-shaped section whose outlet aperture area matches the inlet aperture area in the front plate. All reflecting surfaces were carefully polished to remove tool and abrasive marks as completely as possible. Aluminum reflecting surfaces were then applied by vacuum evaporation.

A full scale light pipe for use at the CNRS Solar Furnace would be constructed using a substrate metal, probably copper, coated by another metal to obtain high optical reflectivities on the interior surfaces. The candidate reflecting materials are listed in Table 2. Silver and Beral have the highest reflectivities. Freshly deposited aluminum also has a high reflectivity, but this deteriorates rapidly as an oxide coating is formed; aluminum may be protected by an evaporated silicon monoxide film but the reflectivity of the coated aluminum surface is about the same as that of an aged surface. From the data in Table 2, it can be seen that silver is the material of choice for two reasons: (1) the highest possible reflectivity is needed to minimize flux losses caused by multiple bounces of light rays in the pipe, and (2) the short exposure times and rather dirty nature of the experiments imply that periodic cleaning of the reflecting surface will be necessary, that the fragile nature of Beral or aluminum films are incompatible with cleaning, but that electroplated silver is capable of being cleaned and



Dimensions in millimeters

Figure 16. Basic light redirecting structure consisting of conical segments.

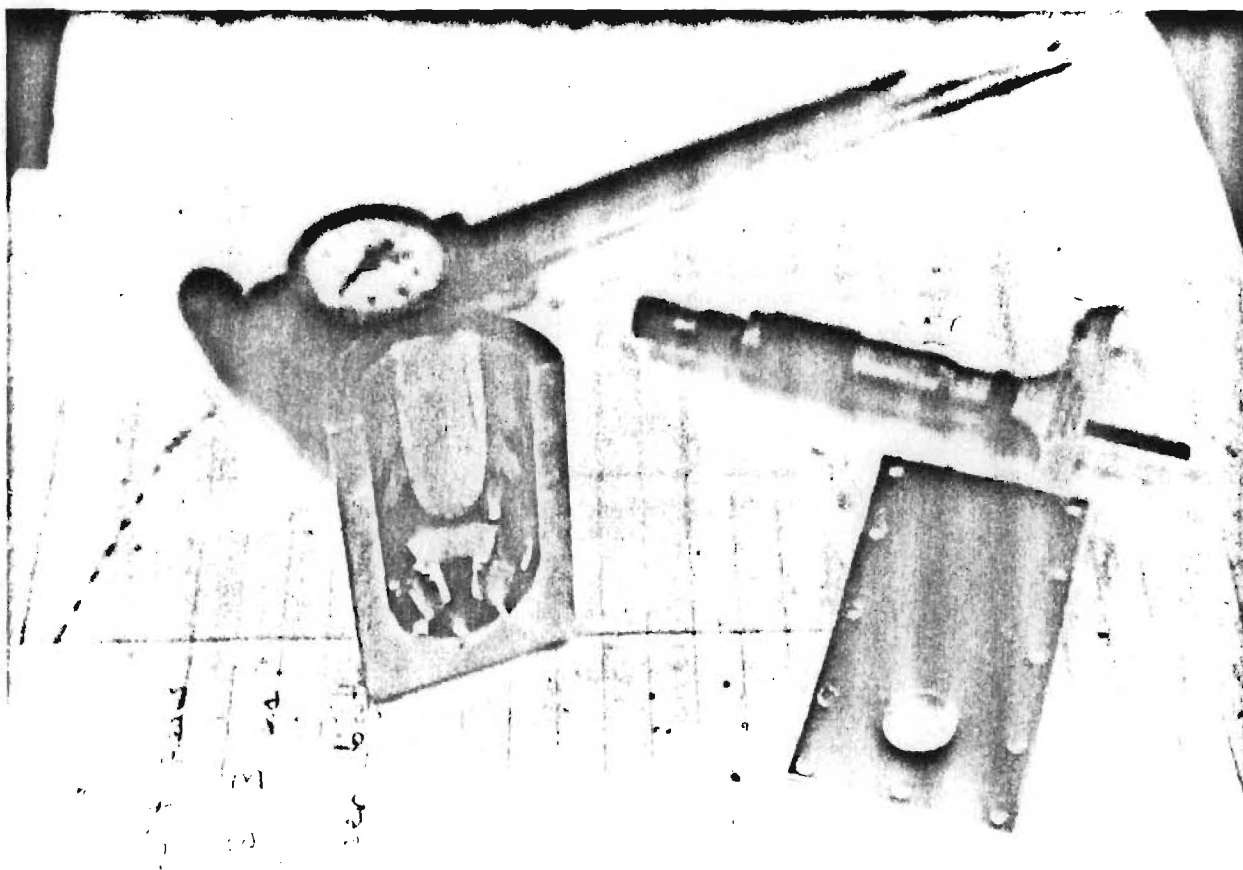


Figure 17. Straight sided light pipe model during fabrication.

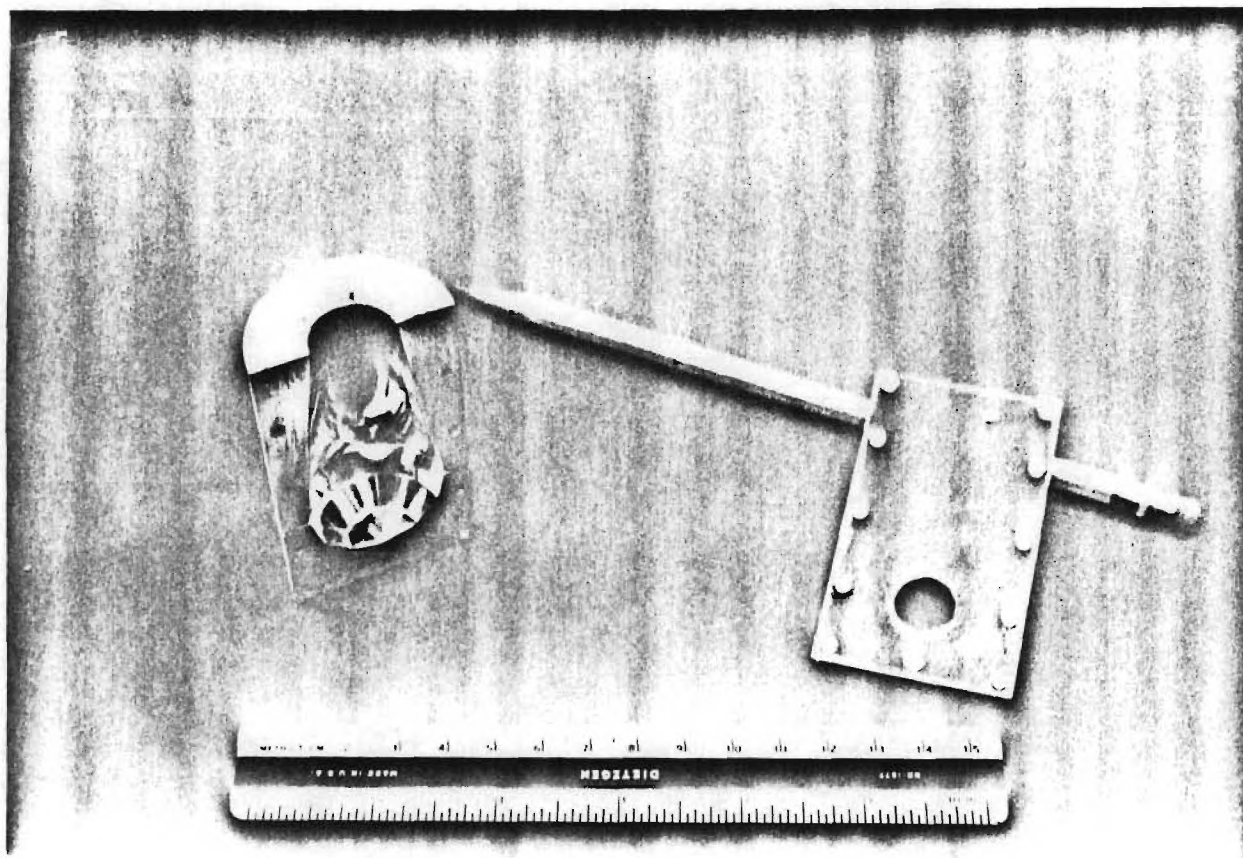


Figure 18. Funnel shaped light pipe model after application of reflecting surface.

Table 2. Reflectivities of mirror materials.

Material	Reflectivity over Visible Spectrum (percent)	Remarks
Silver	90-95 ^a 90-95 ^b	Tarnishes on exposure to atmosphere
Aluminum	75-85 ^a 75-85 ^c	Must be deposited by vacuum evaporation; reflectivity deteriorates if not protected by overcoat
Beral (aluminum-beryllium alloy)	85-88 ^c	Must be deposited by vacuum evaporation; proprietary alloy available from only one source ^e
Rhodium	78-80 ^b 85-87 ^d	Must be deposited by vacuum sputtering; excellent weathering qualities
Chromium	70-75 ^d	Reflectivity deteriorates slowly after exposure to atmosphere
Nickel	70-75 ^d	Reflectivity deteriorates rapidly after exposure to atmosphere; makes good base for evaporated surfaces

NOTES: a. Ref. 7
b. Ref. 8
c. Ref. 9
d. Ref. 10
e. Beral evaporated coatings are manufactured by the Dudley LeRoy Clausing Company of Skokie, Illinois.

polished. The model light pipes were coated with aluminum because this could readily be done on campus without delays associated with issuing a purchase order for commercial plating.

LIGHT PIPE TESTS

The two model light pipes shown in Figures 17 and 18 were tested in the laboratory solar furnace at Georgia Tech; photographs of the experimental apparatus are shown in Figures 19 and 20. The light pipe was supported on a sliding fixture which could be moved perpendicular to the axis of the parabolic dish, placing in the focus either the light pipe's aperture or an "input" calorimeter. An "output" calorimeter was mounted at the light pipe's exit plane. The test pipe was placed in an inverted orientation for experimental convenience, but this did not affect experimental results since the furnace is symmetric about its horizontal axis (the parabola is not truncated as at CNRS).

Results of the experimental measurements are shown in Table 3. The flux values given in the table are averages of five repeated runs in which inlet and outlet fluxes were determined successively. When these were multiplied by the respective inlet and outlet apertures, energy balances could be made for analytical treatment of alternate designs and surface reflectivities. A set of experiments to measure flux distribution over the aperture of one light pipe gave values consistent within about ± 10 percent for the measurement positions selected. The experimental data clearly show that the cylindrical column configuration has smaller optical losses than the cone; it is preferred for this reason as well as because a column of uniform cross section will facilitate analysis of soil blowoff data. The cone-shaped column proved, however, that higher fluxes could be obtained by throttling the output beam. It was impractical to construct a smaller domed reflecting structure because of fabrication and polishing considerations.

LIGHT PIPE ANALYSES

Using the experimental data from the two light pipe models tested on the laboratory solar furnace, it is possible to estimate the output fluxes which might be expected from alternate configurations and surface reflectivities. This extrapolation is based principally on the fact that the energy remaining in a reflected ray after several reflections is

$$F = R^n \text{ or } \log F = n \log R$$

where F = fraction of energy remaining in the beam

R = "gray body" reflectivity of the reflecting surface

n = the number of reflections

In order to model the performance of a light pipe, one must run an energy balance which adequately accounts for all reflective losses. A computer analytical model existing at Georgia Tech was adapted to the light pipe problem. The most important conclusion derived from this model was the fact that approximately 3.0 percent of the incoming rays at the light pipe aperture either missed the aperture or were reflected back through it; of the remaining rays, 96.4 percent emerged at

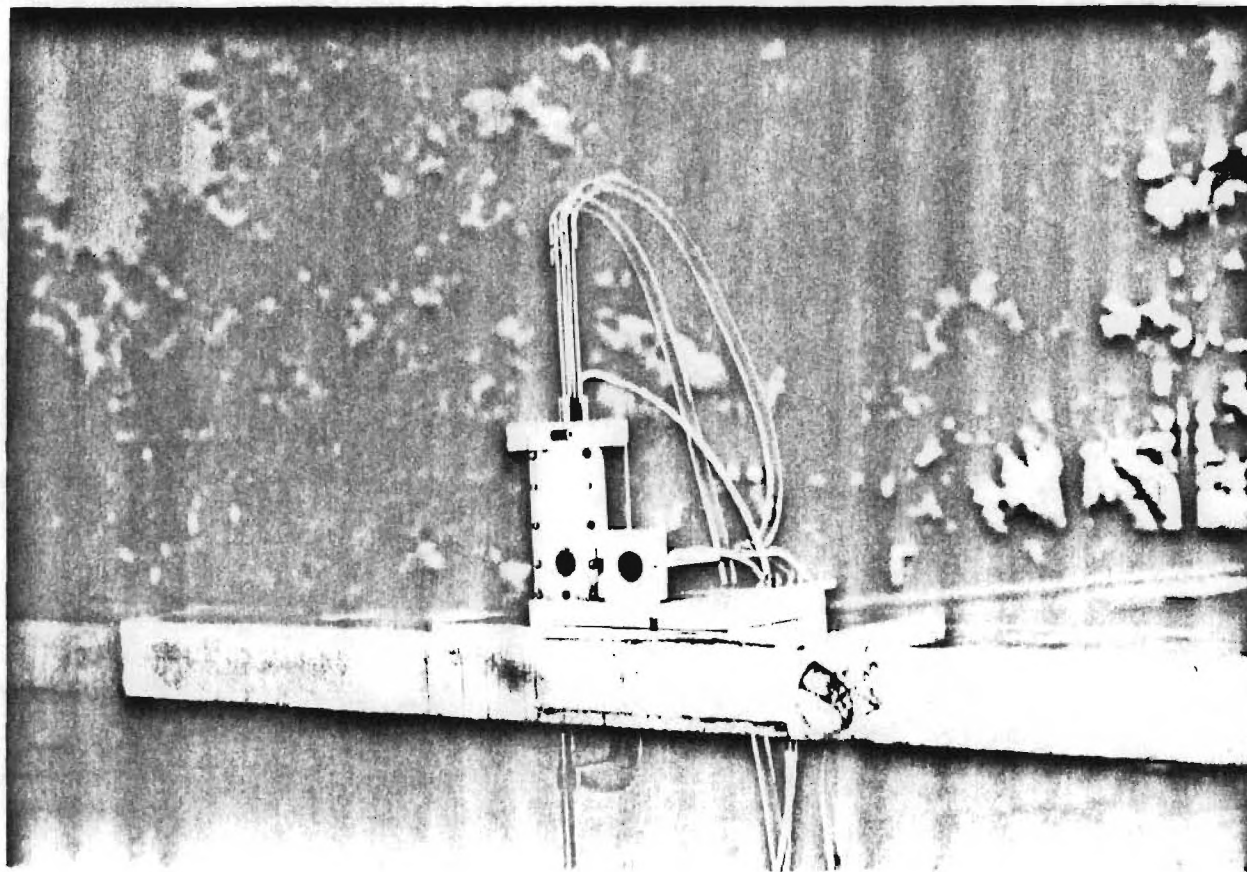


Figure 19. Experimental light pipe and calorimeter assembly.

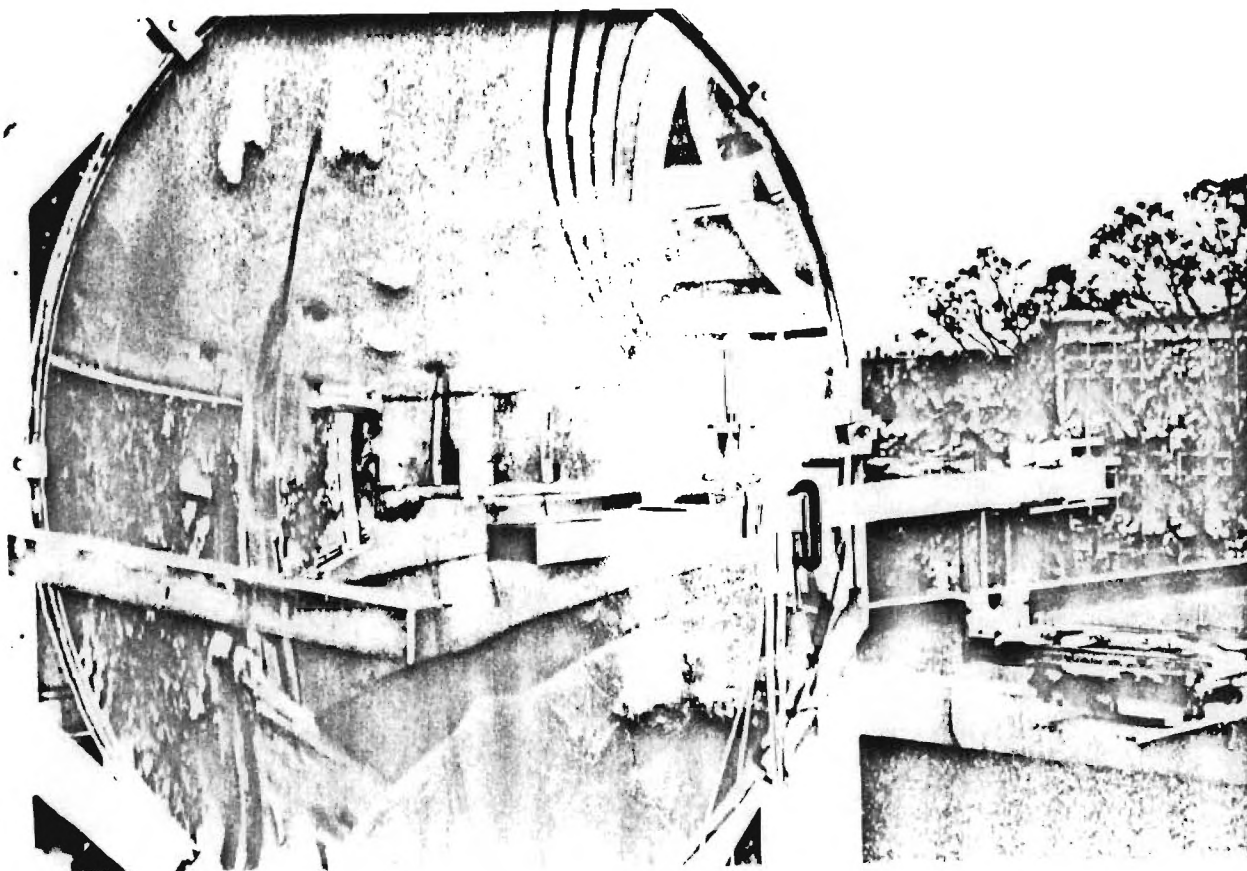


Figure 20. Parabola and light pipe assembly while test is underway.

Table 3. Experimental results of light pipe tests.

Parameter	Cylindrical Column Light Pipe (Figure 17)	Conical Column Light Pipe (Figure 18)
Flux over inlet aperture (cal/cm ² s)	62.9	39.6
Inlet aperture area (cm ²)	1.394	1.394
Energy crossing inlet aperture (cal/s)	87.7	55.2
Flux over outlet aperture (cal/cm ² s)	8.14	8.68
Outlet aperture area (cm ²)	3.645	1.239
Energy crossing outlet aperture (cal/s)	29.7	10.8
Fraction of energy transmitted (percent)	33.9	19.6

NOTES: Aluminum reflecting surfaces; reflectivity 75-85 percent.

Variation in inlet aperture flux was caused by different insolation values on the days tests were conducted.

the exit plane and 0.6 percent were unaccounted for. Since conservation of rays was not obtained in the computer model, it was used only to estimate the net fraction of energy lost through "back reflection."

The remaining analysis of the two light pipe models is traced in Table 4. From the data shown in the last three lines of the table, it is reasonable to expect that fluxes at the sample plane ranging from one-third to two-thirds of the values at the inlet aperture plane can be obtained under the following design conditions:

- (1) The light pipe should have the cylindrical column configuration shown in Figure 17 except that the inlet aperture must be larger with respect to the remainder of the structure; the dimensions of the dome must be adjusted to accommodate the larger inlet aperture.
- (2) For use at the CNRS 1000 kW Solar Furnace, the light pipe inlet aperture should be approximately one solar image diameter (17 cm or 6.7 in.); upon completion of the heliostat realignment program currently being performed by CNRS, this should give an average inlet flux of at least 294 cal/cm²s and an inlet power of at least 270 kW.
- (3) The semi-circular outlet aperture of the light pipe should be equal in area to the inlet aperture (radius of 12 cm or 4.75 in.).
- (4) The light pipe structure should be machined from copper or brass, polished to a high luster with all tool marks removed, electroplated with silver, and polished to a high specular reflectivity.

A preliminary heat conduction analysis has been conducted to evaluate the danger of melting the surface of a light pipe exposed to the peak incident flux at the CNRS Solar Furnace (383 cal/cm²s). This suggests that the light pipe structure should be fabricated with walls on the order of 1 to 2 cm thick but that water cooling should not be necessary for exposure times up to about 10 seconds. Machined copper disks withstood incident fluences of 1,100 to 1,200 cal/cm² during exposures to incident fluxes of about 300 cal/cm²s at the CNRS facility (Ref. 11). The higher reflectivity of a polished, silver-plated surface should permit larger fluences to be accepted, provided the silver remains bright.

Table 4. Analysis of light pipe experiments.

Parameter	Cylindrical Column Light Pipe (Figure 17)	Conical Column Light Pipe (Figure 18)
Energy crossing inlet aperture from Table 3 (cal/s)	87.7	55.2
Net energy into light pipe (0.964 x energy crossing inlet aperture) (cal/s)	84.5	53.2
Energy crossing outlet aperture from Table 3 (cal/s)	29.7	10.8
Fraction of net energy transmitted	0.351	0.203
Reflectivity of aluminum surface from Table 2	0.80	0.80
Average number of reflections for each ray ($n = \log F / \log R$)	4.69	7.15
Reflectivity of silver surface from Table 2	0.92	0.92
Fraction of net energy recoverable with silver surface ($F = R^n$)	0.676	0.551
Maximum fraction of energy recover- able assuming $R_{Al} = 0.75$ and $R_{Ag} =$ 0.95	0.830	0.753
Minimum fraction of energy recover- able assuming $R_{Al} = 0.85$ and $R_{Ag} =$ 0.90	0.507	0.356

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been reached on this research program:

- (1) It is feasible to perform tests for irradiation of soil specimens at the CNRS 1000 kW Solar Furnace. Fluxes incident on the sample plane can be expected to fall within the range of one-third to two-thirds of the values incident at the focal plane of the facility (100 to 200 cal/cm²s at the sample plane). These flux values are sufficiently high to model a significant portion of DNA's desired test range (see Figure 1).
- (2) The fluxes incident at the focal plane of the CNRS 1000 kW Solar Furnace can be turned by hollow light pipes using silver reflecting surfaces on the interior walls. From the viewpoint of optimum light pipe geometry, the vertical column above the sample plane should have a semi-circular cross section of constant area. If this geometry is too great a deviation from the preferred circular or square cross sections, the preferred cross sections might be provided with some sacrifice in flux at the sample plane.
- (3) Vertical slit windows and other measurement devices can be incorporated into the light pipes without significant degradation of optical performance but with increases in equipment complexity. For the first experiments at CNRS, existing automatically timed shutters can be used; these furnish a pulse shape approximately square with respect to time (opening time about 0.1 to 0.2 seconds and closing time about 0.2 to 0.3 seconds).
- (4) Light pipe designs are constrained by the requirement that the inlet and outlet apertures be approximately equal in area; otherwise the optical losses significantly degrade the flux available at the sample plane.
- (5) The double reflector flux turning device, employing a curved redirecting mirror near the focus of the large parabolic mirror, is not feasible for reasons given in this report.
- (6) Fluxes higher than those available at the sample plane of "right angle" light pipes developed on this program may be obtainable if some compromise in experimental test conditions can be permitted; for example, orientation of specimens in a sloping, rather than horizontal, position or the use of tapered light pipes with non-constant cross section.

The engineer in charge of the CNRS 1000 kW Solar Furnace has indicated his willingness to collaborate on soil measurement programs under DNA sponsorship, provided however, that the experimental details and participating personnel must be approved by CNRS prior to initiation of work. It appears that the next step toward performing the required measurements is the testing of a full-scale light pipe at the CNRS facility. Accordingly, Georgia Tech makes the following recommendations:

- (1) Small coupons of light pipe wall structures should be tested at the CNRS Solar Furnace in mid-1979. The coupons would be silver-plated copper and silver-plated brass having diameters of about 5 cm (2 in.) and thicknesses of 1 to 2 cm ($\frac{1}{2}$ to 1 in.). The purpose of the tests would be to assure that the reflecting surfaces will survive exposures to the anticipated incident fluences under actual test operating conditions; incident fluxes should be the highest levels available (about 400 cal/cm²s) and fluences should correspond to exposure times up to about 10 seconds (4,000 cal/cm²). These tests could be conducted during a planned trip to the CNRS Solar Furnace for another research program in April 1979. If it were found that the candidate wall structures could not survive these exposure conditions, then provisions for forced cooling of light pipes would be required.
- (2) During the same trip to the CNRS Solar Furnace, detailed agreements for subsequent test campaigns should be worked out. Since diagnostic techniques for soil blowoff measurements have already been developed by Science Applications, Incorporated; it would be extremely helpful to the Defense Nuclear Agency program if CNRS would permit one representative of SAI to accompany Georgia Tech personnel on subsequent test campaigns; the tests might be conducted under the direction of CNRS and Georgia Tech, with the SAI representative assisting in the area of diagnostic instrumentation.
- (3) Detailed design and construction of a full-scale light pipe for soil tests should be performed. It is presently recommended that the light pipe follow the design conditions given on page 35 of this report, that cooling be accomplished by providing sufficient heat capacity in the walls (sufficient wall thickness) to accept exposures up to about 10 seconds, and that provisions be made for windows, thermocouples, guillotine shutters and other diagnostic equipment as appropriate. Design details of these accessories will be coordinated with SAI under the direction of DNA.
- (4) The full-scale light pipe should be subjected to proof testing at the DOE Advanced Components Test Facility at Georgia Tech in order to demonstrate that it can survive incident fluences chosen to simulate the reflective surface temperatures which will be attained at the CNRS Solar Furnace, to measure the fraction of the input flux which reaches the specimen plane, and to permit development of photographic documentation techniques. Although the flux level and rim angle provided by the ACTF do not match those at CNRS, these tests might prevent mistakes on the first test campaign in France.
- (5) An initial test campaign at the CNRS Solar Furnace should be conducted in late 1979 if the arrangements and light pipe tests are successfully completed. This work, like the coupon tests described above, might be accomplished during a trip which is scheduled for another research program (sharing of travel and other expenses would benefit both programs). In these tests, soil samples would be irradiated and all data collection procedures would be employed. The results of this work would assist in defining the scope of subsequent research and test activities.

- (6) A continued limited-scale effort for development of test and instrumentation techniques should be conducted. Alternate reflector designs for flux turning, very small thermopiles for temperature measurement, particle characterization by infrared television, other ideas which might be useful for soil blowoff measurements have been suggested during the course of this research program. A limited investment in further exploration of these subjects might ultimately yield useful testing capability, although these activities must not impede the basic goal of conducting soil tests in late 1979.

SECTION IV

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FINAL REPORT

DNA _____

TECHNIQUES FOR INVESTIGATING MATERIALS IN A RADIANT HEAT ENVIRONMENT

1 February 1979

Prepared for

**DEFENSE NUCLEAR AGENCY
Washington, D. C. 20305**

Under

Contract No. DNA 001-78-C-0261

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GEORGIA INSTITUTE OF TECHNOLOGY

**A Unit of the University System of Georgia
Engineering Experiment Station
Atlanta, Georgia 30332**



1983



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Block 20, ABSTRACT (Continued)

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A variety of light pipe configurations and a multiple mirror design were considered for the proposed application. Models of two light pipes were built and tested; results indicate that one-third to two-thirds of the available flux level can be delivered to the soil specimen plane. It is recommended that small light pipe surface coupons be tested at CNRS in mid-1979 and that a prototype light pipe assembly be constructed and tested with soil samples in late 1979.

SUMMARY

The long range objective of this program is to measure quantitatively the behavior of soil specimens while they are subjected to simulated thermal pulses from nuclear weapons. The CNRS 1000 kW Solar Furnace in France is capable of supplying the highest fluxes of concentrated solar radiation available at any facility in the world. The immediate purposes of this research program were to develop optical devices by which the soil measurements might be adapted to the CNRS facility, to perform scale model tests on these devices using a laboratory solar furnace, and to plan a series of tests at the CNRS facility.

A variety of light pipe configurations and a multiple mirror design were considered for the proposed application. Models of two light pipes were built and tested; results indicate that one-thirds to two-thirds of the available flux level can be delivered to the soil specimen plane. It is recommended that small light pipe surface coupons be tested at CNRS in the mid-1979 and that a prototype light pipe assembly be constructed for testing with soil samples in late 1979.

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SECTION I

INTRODUCTION

Prediction of the effects of nuclear weapons is a subject of considerable interest to the Defense Nuclear Agency. In order to perform these predictions by analytical methods, it is necessary that certain transport properties of the media surrounding the point of detonation be known; the transport properties of the atmosphere near the surface of the ground are of particular interest in this program. The overall objective of the present research effort was to develop techniques for measuring atmospheric properties near the ground surface during and shortly after the arrival of a simulated nuclear thermal pulse. Specifically, methods for obtaining high fluxes of radiant energy on a horizontal specimen were addressed.

DESCRIPTION OF THE PROBLEM

When a nuclear weapon is detonated in the atmosphere, energy is released by several mechanisms. Within the first 10^{-8} second or so, depending on yield, energy appears as kinetic energy of the materials of which the weapon was made, internal energy of these particles, and electromagnetic radiation of wavelengths ranging from the infrared region of the spectrum to x-rays (Ref. 1). Within less than one second, most of this energy is absorbed by the atmosphere within a few feet of the point of detonation and results in the creation of a spherical region containing air and weapon debris at temperatures of tens of millions of degrees and pressures of millions of atmospheres. This high-temperature, high-pressure region is known as the fireball, and it in turn releases energy as thermal radiation, a shock front propagated through the atmosphere, and as gamma radiation or high-energy x-rays. The fireball surrounding the point of detonation is effectively the source of the thermal radiation and shock phenomena.

The thermal radiation emitted from the surface of the fireball travels at the speed of light in all directions. The radiant energy arriving at the ground has roughly the wavelength distribution of sunlight arriving at the ground although the radiant intensity is many times greater than sunlight and diminishes in inverse proportion to the square of the distance to the fireball's surface. The radiant energy arrives at the ground almost immediately and appears as a pulse which rises very quickly and decays more slowly over a period of several seconds; the pulse duration is dependent on weapon yield. If the site of interest on the ground is sufficiently near ground zero and the weapon yield is sufficiently large, the thermal energy pulse can disturb the soil and the atmosphere immediately above the surface so that the transport properties of the atmosphere are altered. The air temperature may be increased and water vapor and particulate materials may be ejected into the air.

The rapidly expanding high-pressure gases within the fireball couple to the surrounding atmosphere and generate a radially expanding shock wave which travels initially at many times the speed of sound in air but much slower than the speed of light. The propagation of the shock wave in the air is affected by the local Mach number ahead of the shock front, the heat capacity of the air, and the pressures ahead of and behind the shock front; the local Mach number is governed by the heat capacity, density and temperature of the air (Ref. 2). Thus, the heat

capacity, density, pressure and temperature ahead of the advancing shock front are the transport properties governing the movement of the front. If these properties have been altered by the action of the thermal pulse before the shock front arrives, then the behavior of the shock will be altered in comparison to its behavior in undisturbed air.

The phenomenon known as the "Mach Effect" illustrates the importance of shock wave modification (Ref. 1) , paragraphs 2.33-2.35-3.20-3.25). The incident (or initial) shock propagates radially from the point of detonation until it contacts the ground directly beneath the fireball. After the incident shock contacts the ground, it continues to move through the atmosphere and a reflected shock wave develops behind the incident wave. The speed of the reflected wave, however, is greater than the speed of the incident wave because it is traveling through air which has been disturbed by the passage of the incident wave. The reflected shock wave soon catches the incident wave and they form a merged shock wave known as a "Mach Stem." The Mach Stem moves through undisturbed air; it is characterized by an overpressure (pressure behind the wavefront) on the order of twice the overpressure of the initial wave alone (Ref. 1, paragraph 3.18). Thus the modification of the propagation medium (air) by the initial shock has resulted in development of a merged shock wave which has about twice the overpressure of the initial wave. The potential for blast damage to targets on the ground is correspondingly increased. It is clear that alteration of the transport properties of the atmosphere can cause significant perturbations in nuclear weapons effects.

When the thermal radiation from a nuclear explosion impinges on a heat-absorbing surface, such as desert, coral, or asphalt, a hot layer of air, known as a "thermal layer" is produced (Ref. 1, paragraph 3.72-3.73). The thermal layer often includes smoke, dust, and other particulate matter. It forms before the arrival of the shock wave from an air burst, and interaction of the wave with the heated layer may affect the reflection process to a considerable extent. Under certain conditions, an auxiliary shock wave, known as a "precursor," can form and move ahead of the main incident wave. Severe modification of the usual blast wave characteristics may occur within the precursor region. Precursor formation is not to be expected over non-dusty and heat-reflecting surfaces, such as concrete, snow, ice, or water.

The problem of interest in the present work is the measurement of the changes in atmospheric properties above a soil surface exposed to a simulated nuclear thermal pulse. The data sought are the transport properties of the atmosphere (temperature, density, concentration and description of materials ejected from the specimen surface) and documentation of the behavior of the system during exposure to high radiant heat fluxes. To accomplish this, one must devise suitable means for exposing the sample to radiant energy at sufficiently high flux levels.

DEFINITION OF TEST REQUIREMENTS

Since the wavelength distribution of thermal radiation from a nuclear explosion fireball is roughly similar to the wavelength distribution of sunlight at the earth's surface, concentrated solar radiation is suitable for simulating nuclear thermal pulses. The problem is to achieve sufficiently high incident fluxes of sunlight to adequately simulate the peak fluxes of the fireball's thermal pulse. For many years, large solar furnaces have been used for

measurements of this type; two of the world's major solar test facilities were constructed primarily for this purpose: the U. S. Army Solar Furnace at White Sands, New Mexico, and the French Army Laboratoire Central de l'Armement at Odeillo, France. These two solar furnaces collect on the order of 25 to 50 kW of thermal power.

The desired measurements may be conducted by exposing specimens of soil to pulses of concentrated solar radiation generated by solar furnaces. Science Applications, Incorporated has conducted tests of this type on soil specimens for the Defense Nuclear Agency at the U. S. Army White Sands Solar Furnace in New Mexico (Ref. 3). These studies are generally known as "soil blowoff phenomena" measurements and involve determination of such parameters as soil and air temperature, type and quantity of materials ejected from the specimen, blowoff velocities, etc., while the specimens are irradiated in the solar furnace. At White Sands, incident radiant fluxes up to about 60 cal/cm²s were achieved. Smoke was emitted from nearly all soil types at fluences above a threshold of about 5 cal/cm² (fluence = flux x time), small particles were emitted from most soil types at fluences in the range of 5 to 25 cal/cm², jets or flakes were explosively emitted from soils containing abundant clays at fluences in the range of 25 to 50 cal/cm², and steam was emitted from all moist soils. The fluxes available at the White Sands Solar Furnace, however, were not sufficiently high to adequately cover the range of experimental interest.

The size and optical configuration of the CNRS 1000 kW Solar Furnace at Odeillo, France are substantially different from those at White Sands. The thermal power available at the focal zone is about 40 times as large (1,000 kW versus 26 kW) and the peak heat flux is about four times as large (1,600 W/cm² versus 360 W/cm²). Thus, it should be possible to conduct tests over a much wider range of incident fluxes and fluences at the CNRS facility than at the White Sands facility, if certain experimental requirements can be met. These requirements, defined by the Defense Nuclear Agency and its contractors concerned with the soil blowoff phenomena problem, are:

- (1) The soil sample should lie in a horizontal plane with the incident radiation arriving downward from a direction approximately normal to the sample plane.
- (2) The atmosphere above the soil should be surrounded by a column with reflecting walls so that the atmosphere appears to be an infinite medium; the height of the column should be two to four meters.
- (3) The linear dimension(s) of the sample should be 15 to 30 cm (6 to 12 inches); a round or square sample configuration is preferred.
- (4) The transport properties of the atmosphere must be determined as functions of time and height above the sample plane, beginning at the time of initiation of the thermal pulse and ending at the time of shock wave arrival for the weapon parameters under consideration.
- (5) The soil behavior must be documented photographically and particle samples should be collected at various heights above the specimen plane.

- (6) The optical system used to turn or otherwise process the beam of concentrated solar radiation arriving at the focal zone of the solar furnace must cause a minimum attenuation of the incident flux.

The Defense Nuclear Agency has defined the following experimental conditions as the range of interest for soil blowoff phenomena experiments:

- (1) Weapon yields: 1 kT and 1 MT (kT - 1 kiloton of TNT)
- (2) Scaled ranges: $185 \text{ ft/kT}^{1/3}$ to $600 \text{ ft/kT}^{1/3}$
- (3) Heights of burst: about $50 \text{ ft/kT}^{1/3}$ to $600 \text{ ft/kT}^{1/3}$

These scaled ranged and heights of burst are represented by the rectangular shaded area shown in Figure 1. It is necessary to determine whether a significant portion of this experimental range can be simulated at the CNRS 1000 kW Solar Furnace.

Such an estimate can be made if one assumes that certain power levels are available at the CNRS facility, then estimates the incident fluxes which might be expected on the ground using data in Reference 1. A sample calculation for one data point is given for illustration:

- (1) Assume that the average power level over a 15 cm (6 inch) diameter circular area at the focus of the solar furnace is $294 \text{ cal/cm}^2\text{s}$ (Ref. 4).
- (2) The geometry of the system is shown in Figure 2. If there is no atmospheric attenuation, the thermal power may be regarded as spread uniformly over the surface of a sphere of area $4\pi R^2$, where R = the distance from the explosion (Ref. 1, paragraph 7.99).
- (3) The maximum rate of thermal emission from the fireball is given by $P_{\text{max}} = 4 W^{1/2} \text{ kT/s}$, where W = the weapon yield in kT (Ref. 1, paragraph 7.92) and the explosion of a 1 kT weapon releases 10^{12} calories (Ref. 1, Table 1.41).
- (4) The maximum flux arriving at the target is given by:

$$F_{\text{max}} = \frac{(P_{\text{max}})(\cos \phi)}{A_{\text{sphere}}}$$

Where the angle ϕ is defined in Figure 4. Also,

$$\cos \phi = \frac{\text{height of burst}}{\text{range}}$$

- (5) The two equations above may be combined to relate the range and height of burst which can be simulated with the assumed maximum flux:

$$\text{height of burst} = (\text{range})(\cos \phi) = \frac{4\pi (\text{range})^3 F_{\text{max}}}{P_{\text{max}}}$$

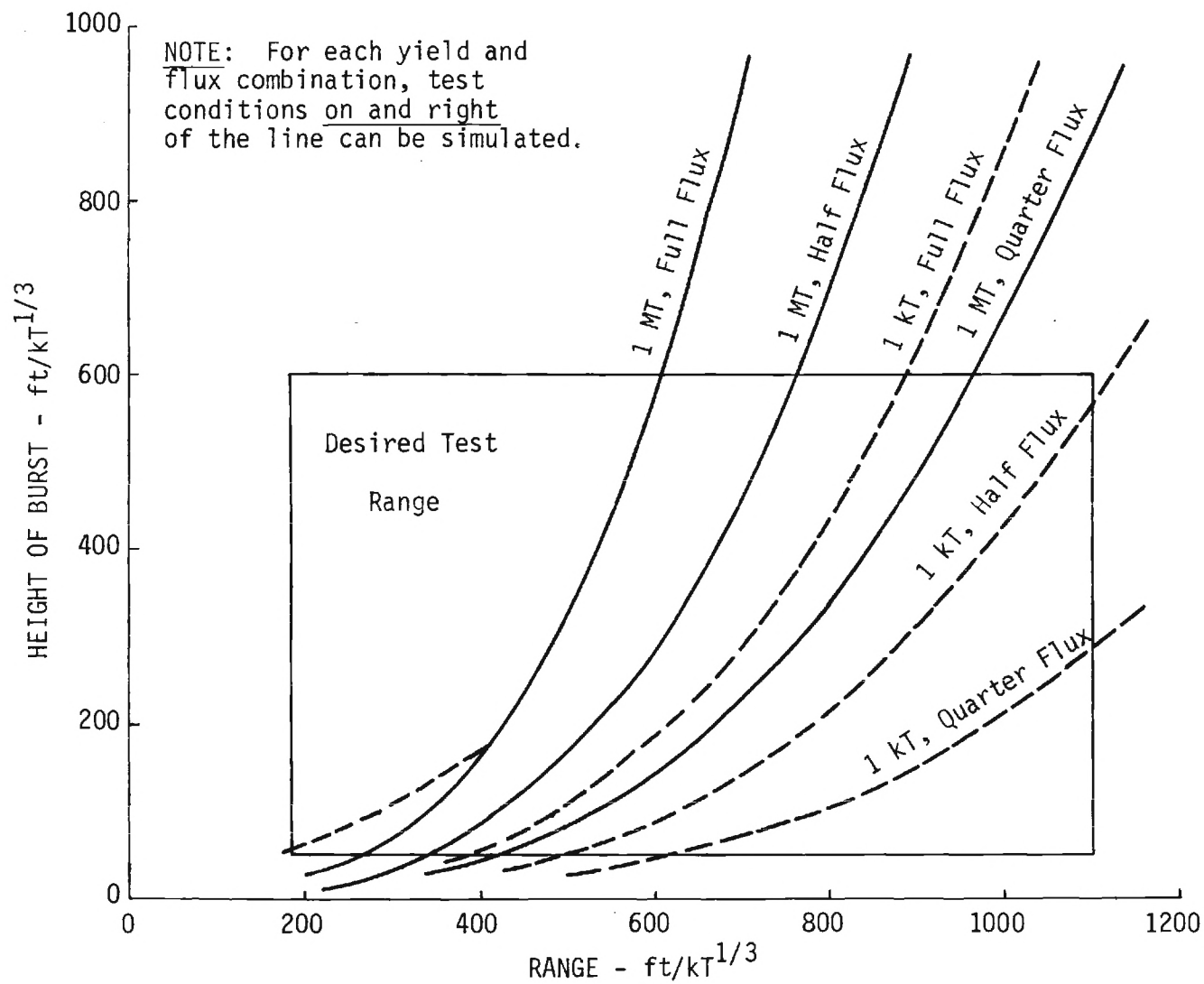


Figure 1. Scaled ranges and heights of burst for measurements of soil blowoff phenomena.

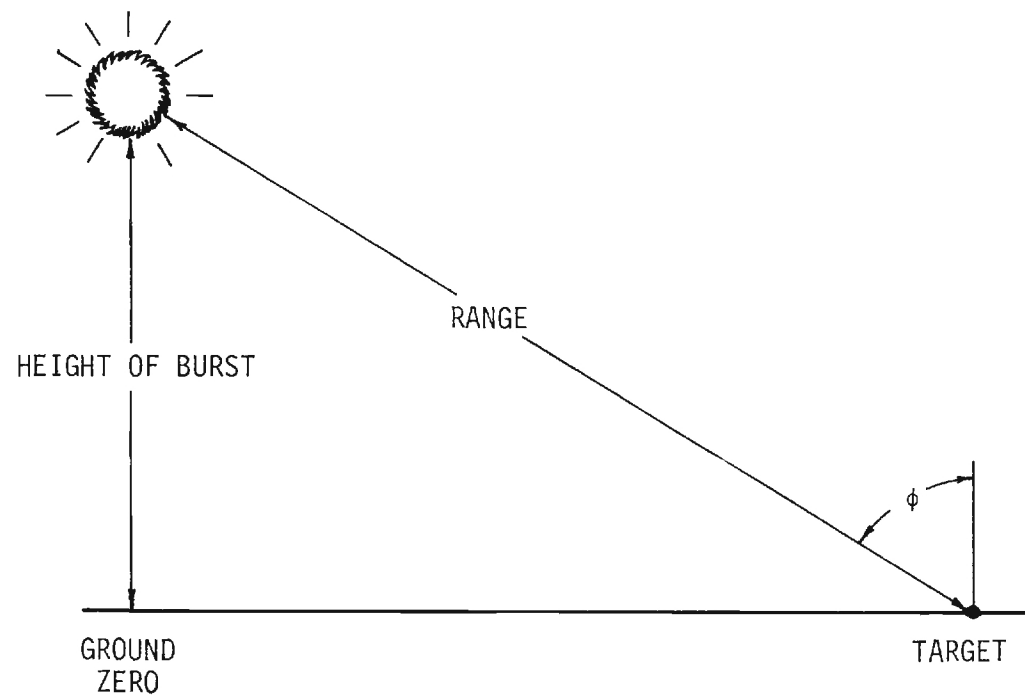


Figure 2. Geometry for calculation of peak heat flux at target on ground.

$$= \frac{4\pi (30.48 \text{ cm/ft})^2 (\text{range ft})^3 (294 \text{ cal/cm}^2\text{s})}{(P_{\text{max}} \text{ kT/s})(10^{12} \text{ cal/kT})}$$

where the height of burst and range are expressed in feet and P_{max} is expressed in kT/s.

- (6) For a sample data point, set $W = 1 \text{ kT}$ and the range = 800 feet. Then $P_{\text{max}} = 4 \text{ kT/s}$ and the height of burst = 439 feet.

The curves in Figure 1 overlaying the shaded area were constructed using the procedure described above. The curves represent weapon yields of 1 kT and 1 MT with maximum incident fluxes corresponding to the average available over a 15 cm (6 inch) diameter circle at the focal plane of the CNRS 1000 kW Solar Furnace (294 cal/cm²s), one-half this average flux, and one-quarter this average flux. If the specified incident fluxes can be attained on the specimen surface, the desired thermal pulse simulation can be performed for combinations of weapon range and height of burst lying on and to the right of the respective curves. Figure 1 shows that the 1 kT yield is the more difficult to simulate and that loss of flux caused by beam-turning devices will severely limit the range of desired test conditions which can be observed.

For high-yield bursts and short ranges, the shock wave will arrive at the target before the thermal pulse reaches its maximum intensity. This fact limits the maximum intensity required to simulate such cases and slightly increases the portion of the shaded area in Figure 1 which can be simulated at the CNRS Solar Furnace. This small effect operates only at the lower end of the 1 MT curves, and is shown by a dashed line for the 1 MT, Full Flux case.

CHARACTERISTICS OF THE CNRS 1000 KW SOLAR FURNACE

The CNRS Solar Furnace can attain, by far, the highest heat fluxes of any solar test facility in the world. Since achieving the highest possible fluxes is seen to be the overwhelming need for further soil blowoff phenomena tests, this facility is clearly preferred for further testing. The most formidable technical problem to be solved is the turning and collimation of the radiation beam incident on the focal plane. The solar furnace, illustrated schematically in Figure 3, employs 63 flat mirrors (heliostats) which track the sun and redirect a uniform beam of radiant energy onto the fixed parabola. The parabola, which is supported on the north side of a laboratory building, concentrates the radiant energy to a focal point. The focal point is positioned in a smaller building between the heliostats and the concentrating paraboloid dish. It is clearly seen in Figure 3 that the optical axis of the system is horizontal; since it is desired that radiation arrive on the soil specimen from a vertical direction, it is necessary to turn the incident beam through an angle approaching 90 degrees.

Another feature which is evident in Figure 3 is the convergence of the incident beam at the focal point. This is illustrated more specifically in Figure 4 which shows the geometry of the focal point with respect to the paraboloid concentrator. This wide-aperture characteristic of the CNRS Solar Furnace is in large measure responsible for the very high incident fluxes available there. The maximum flux available in an optical system increases as the diameter to focal length ratio increases; this ratio at the CNRS facility was chosen to give fluxes

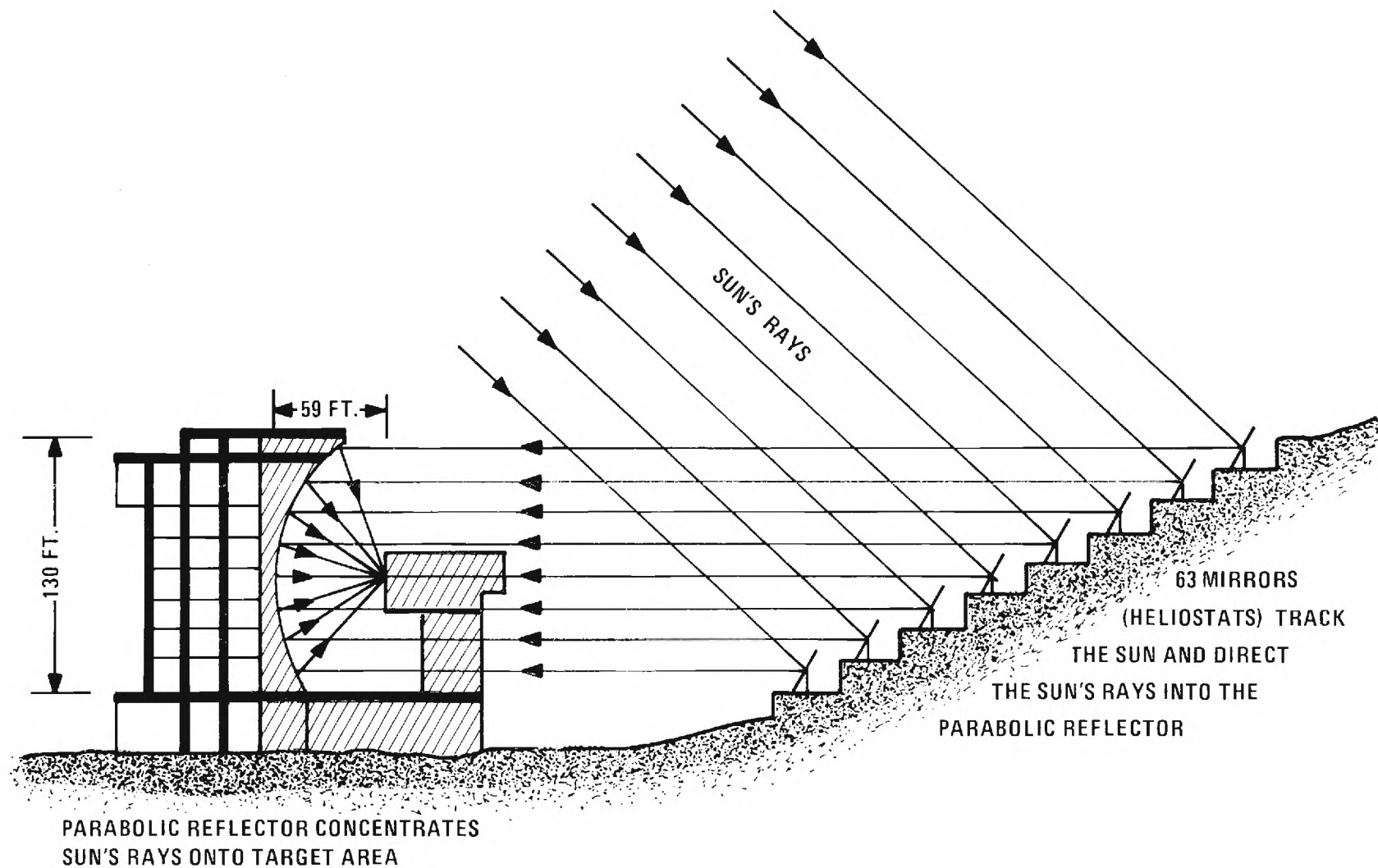


Figure 3. Schematic diagram illustrating operation of the CNRS Solar Furnace.

near the maximum theoretical values on a plane passing through the focus and perpendicular to the optical axis (Ref. 5). (A camera lens is an analogous optical device in which the light gathering power is proportional to the area to focal length ratio.) Since wide angle radiation represents an important fraction of the energy arriving at the focal plane, any optical device used to turn and collimate the beam must adequately recover this radiation component.

Figure 5 shows an incident flux map for the CNRS Solar Furnace. The map is on a plane passing through the focus and tilted back 25 degrees from the vertical; this tilt angle compensates somewhat for the truncation of the bottom of the parabolic concentrator and gives the most uniformly round flux contours. A tilted focal plane is advantageous in the present case because the beam need not be turned a full 90 degrees to achieve a vertically downward direction. The square aperture drawn in Figure 5 illustrates the approximate specimen size desired for soil blowoff tests.

Figures 6 and 7 show the CNRS focal building as viewed from the west. The scale drawing in Figure 7 illustrates the position of the focal point and a conceptual representation of a light pipe and specimen. The two floor levels available for setting up experiments would permit a vertical column length up to about four meters (14 feet), although optical loss considerations make it unlikely that such a long column would be used.

Figures 8 and 9 illustrate the focal room at the CNRS Solar Furnace as seen from the paraboloid concentrator. (These photographs were made in September 1978.) In Figure 8, the sample to be irradiated is the small, hexagonal radar array at the center of the picture. It is surrounded by a water-cooled aluminum shield which masks the unwanted radiant energy around the sample. Two water-cooled, moveable panels which serve as shutters are on either side of the sample; these open in about 0.1 second and close in about 0.3 second under electronic control. The structure in front of the sample, covered with aluminum foil, is a microwave receiving antenna and supporting boom. In Figure 9, the moveable shutters are closed and the solar furnace is in operation; the area in the vicinity of the focal point is thus very brightly illuminated. As seen in Figures 6 through 9, the physical arrangement of the CNRS Solar Furnace provides for great flexibility in the design and testing of experimental hardware.

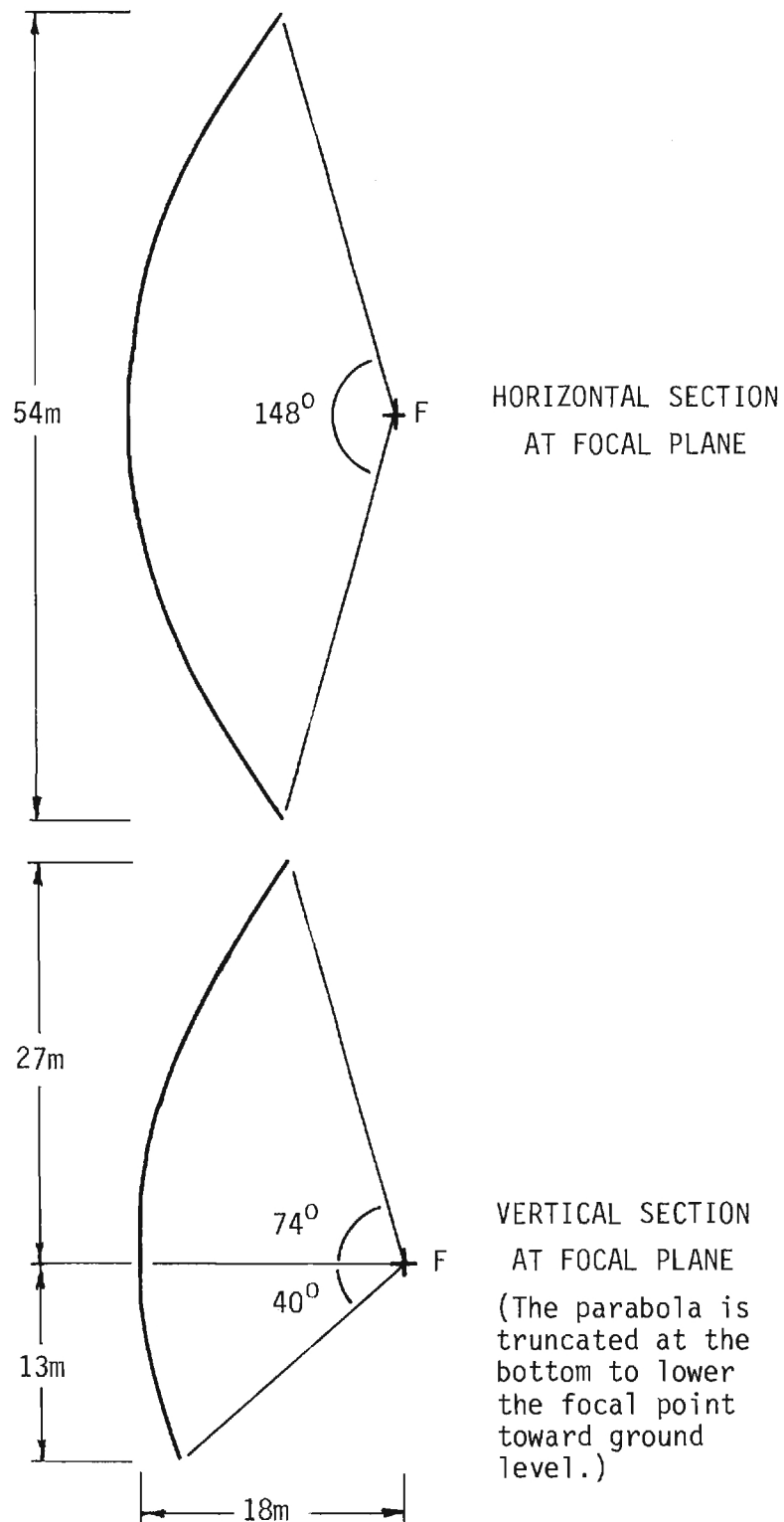


Figure 4. Geometry of focal point with respect to parabola at CNRS Solar Furnace.

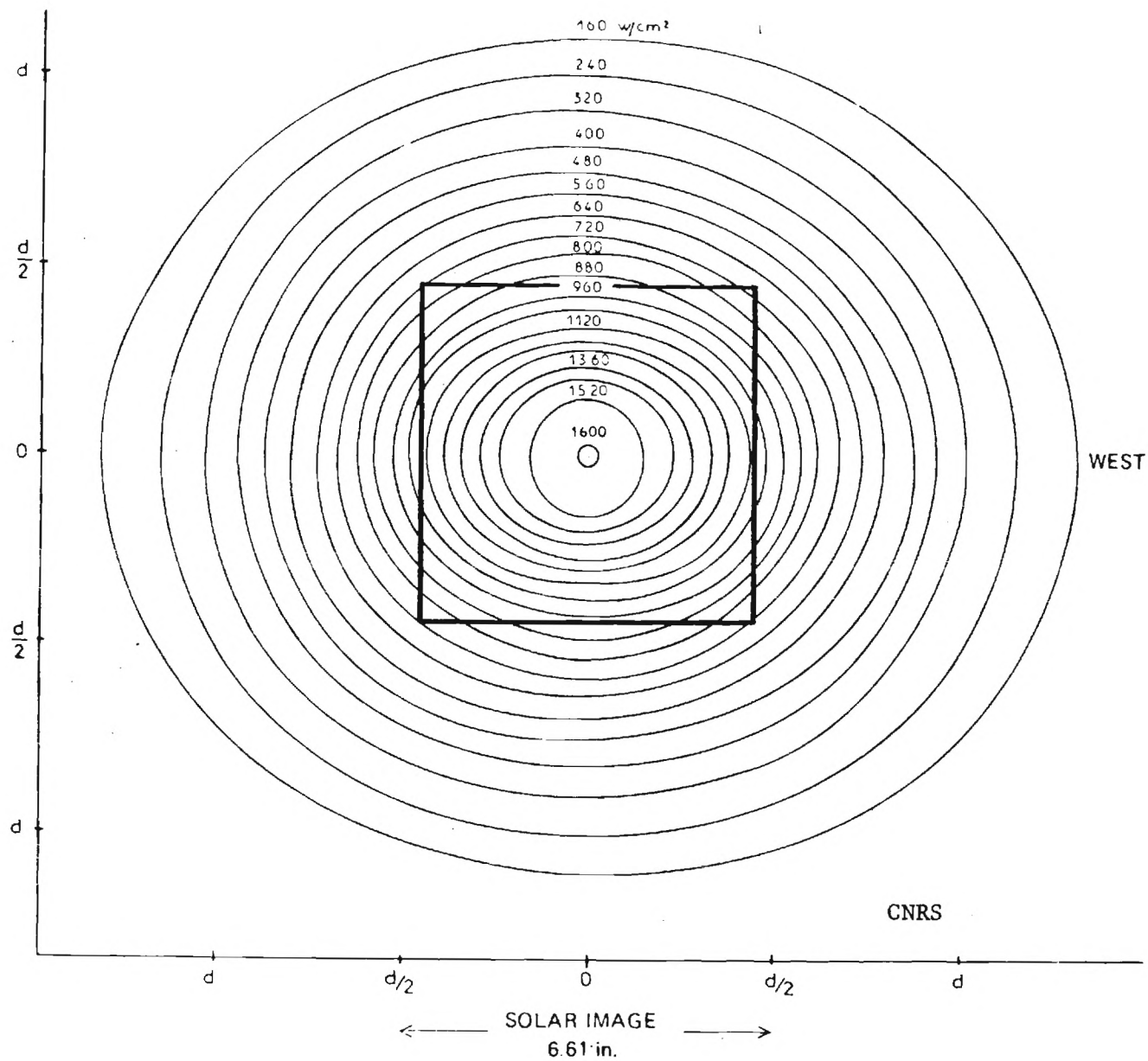


Figure 5. Incident flux map for CNRS 1000 kW Solar Furnace. (A 15 cm (6 inch) square aperture is shown at the center.)

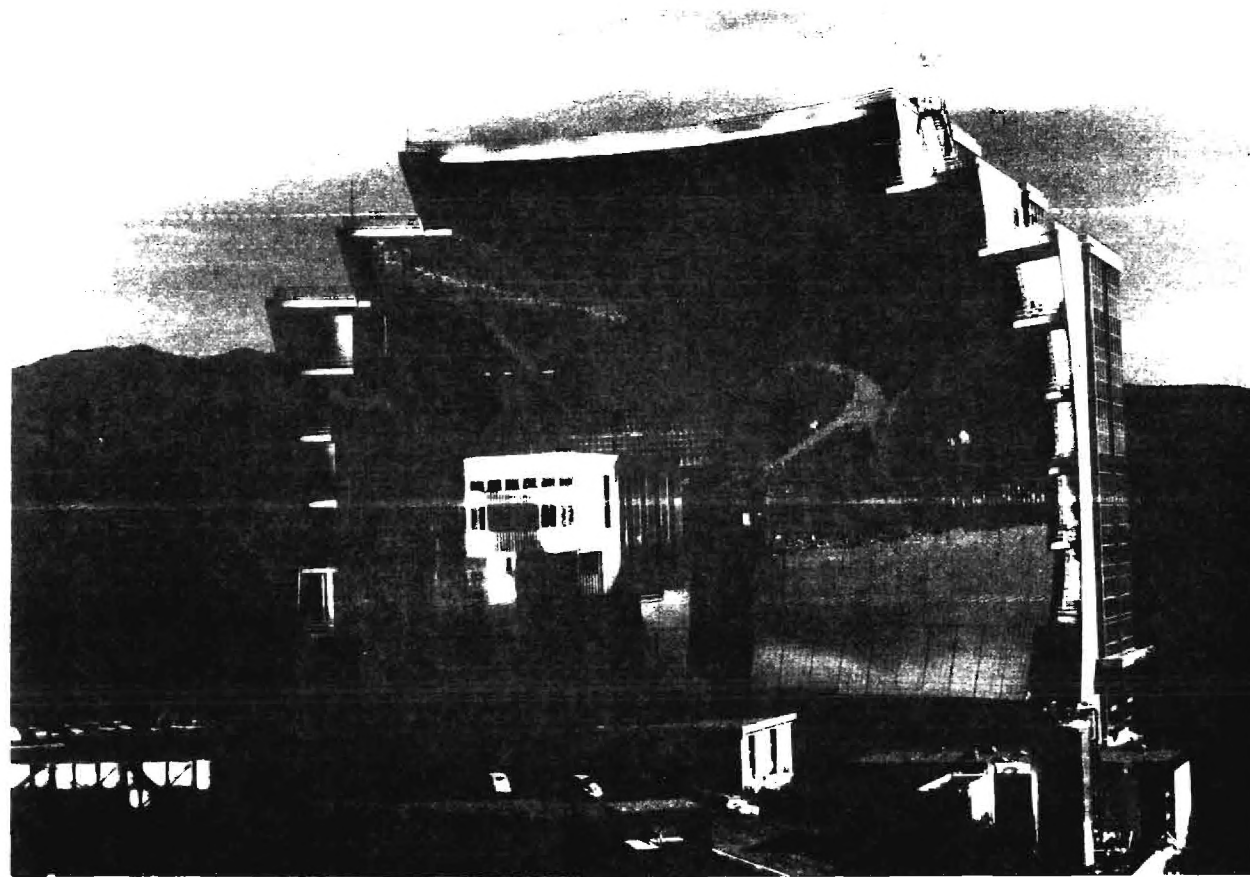


Figure 6. Parabolic concentrator and focal building at CNRS 1000 kW Solar Furnace.

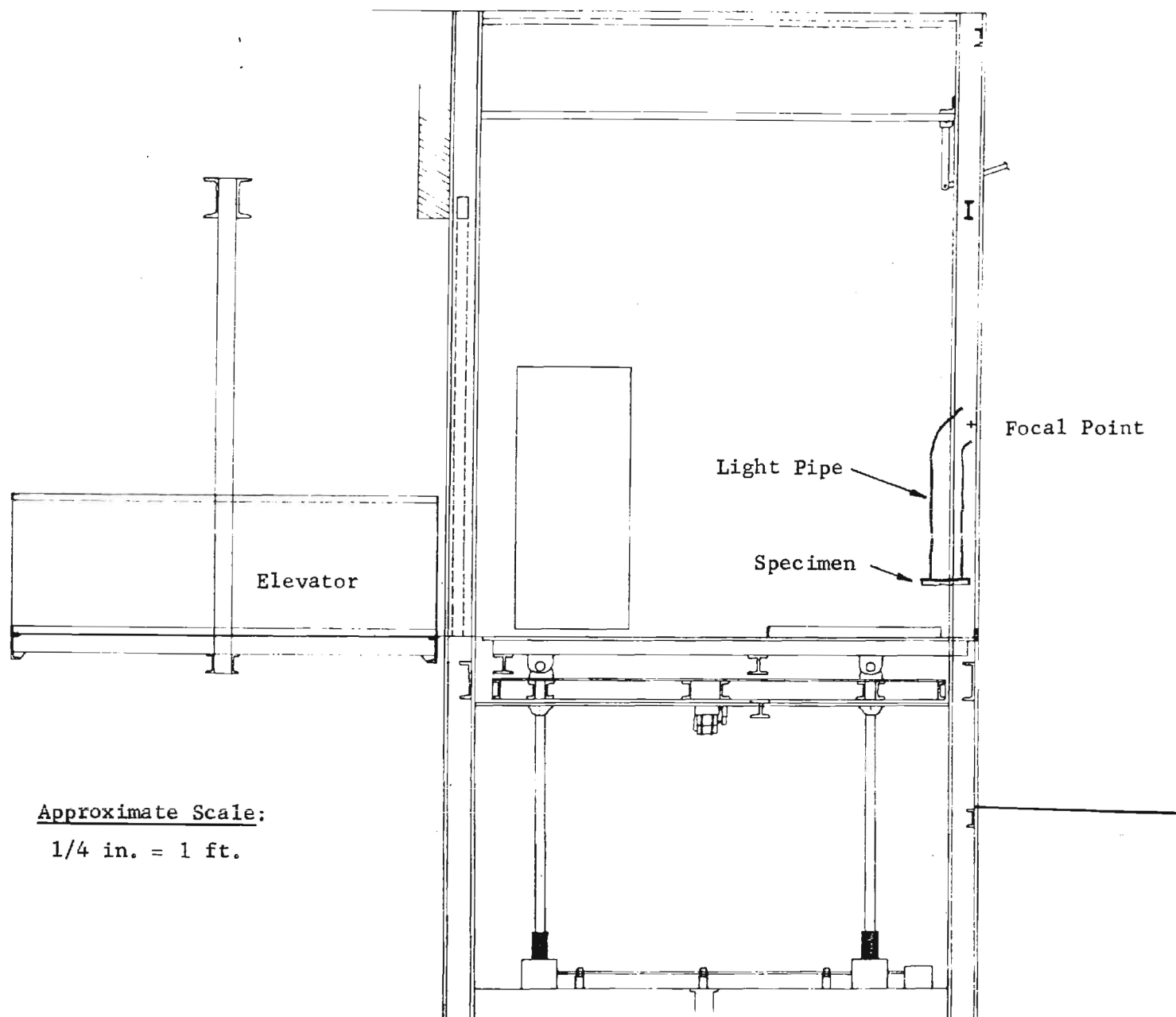


Figure 7. West side elevation of focal building at CNRS Solar Furnace.

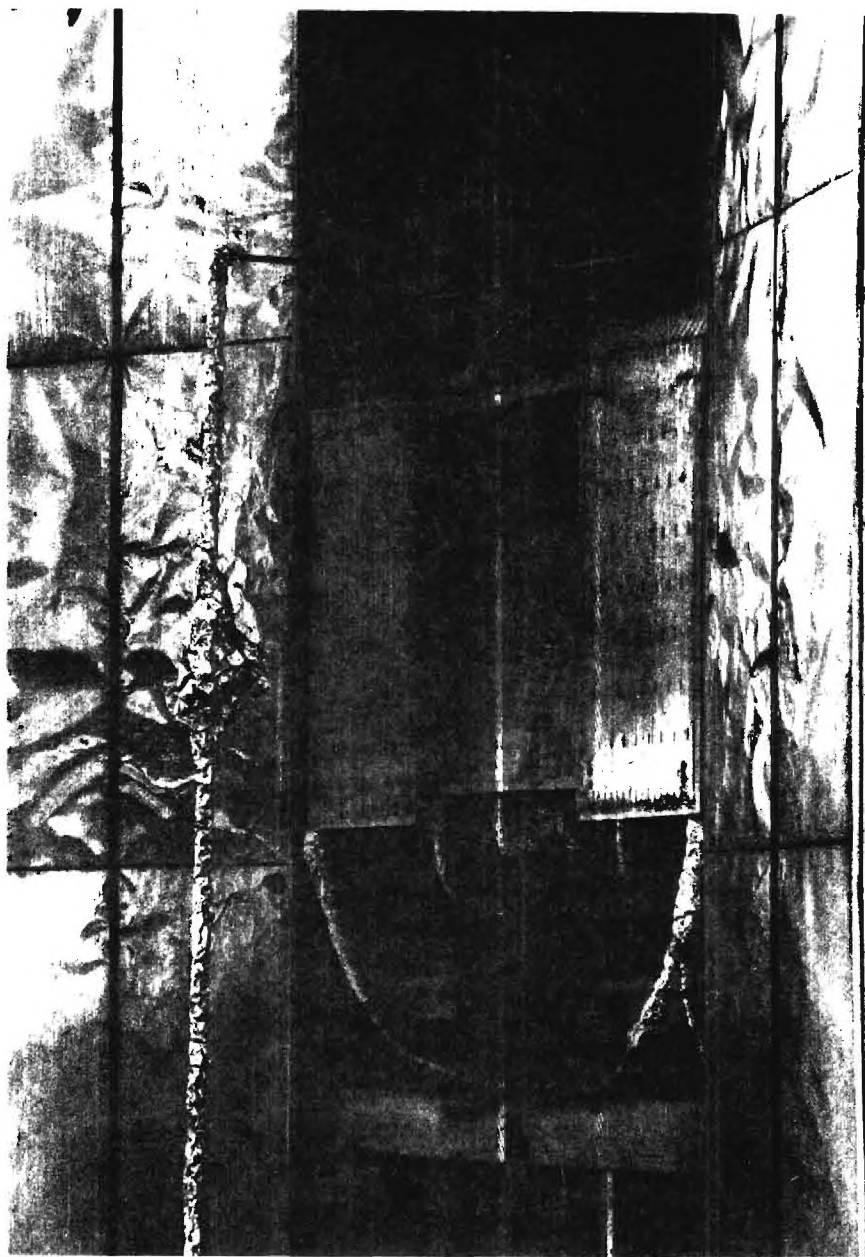


Figure 8. Specimen, water-cooled shields and shutters in focal room at CNRS Solar Furnace.

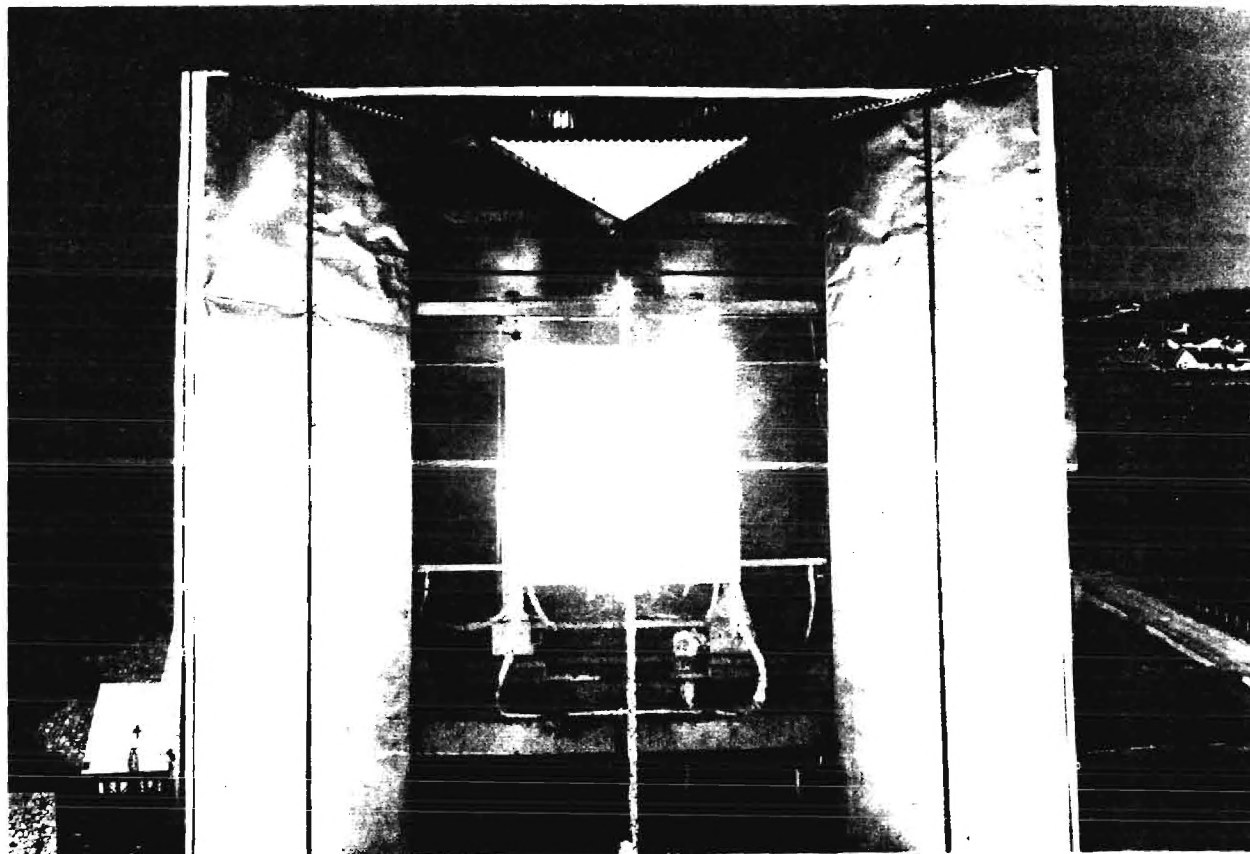


Figure 9. Focal room at CNRS Solar Furnace with shutters closed.

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SECTION II

EXPERIMENTAL WORK

CONTRACT OBJECTIVES

This contract was intended to explore the feasibility of turning and collimating the concentrated beam of solar radiation available at the CNRS 1000 kW Solar Furnace, in order to perform measurements of soil blowoff phenomena. Since it was not clear that such operations on the beam could be done without suffering prohibitive flux losses, this program was designed to apply a limited amount of effort and funds to the problem before committing major resources for a full-scale test program. The research contract was a combination design and experimental testing effort with the following defined objectives:

- (1) To develop techniques for supplying concentrated solar radiant energy to a soil specimen lying in a horizontal plane in a manner which simulates the thermal pulse from a nuclear weapon,
- (2) To characterize the optical performance of the equipment developed in pursuit of the objective above, using scale models and a laboratory solar furnace,
- (3) To plan a series of tests to be conducted in collaboration with the Centre National de la Recherche Scientifique in France and to coordinate these plans with CNRS, the Defense Nuclear Agency, and other agencies and contractors as CNRS and DNA may suggest.

LABORATORY-SCALE SOLAR FURNACE

A small solar furnace on the campus of the Georgia Institute of Technology was used for evaluation of scale model optical hardware developed on this program. This solar furnace is shown in Figure 10 and consists of a tracking heliostat and a paraboloid dish concentrating reflector. The geometric details of the concentrating dish, a military surplus searchlight reflector, are shown in Figure 11. Comparison of Figure 4 and Figure 11 shows that the CNRS and laboratory solar furnaces have rim angles of 74 and 62 degrees, respectively. At the CNRS Solar Furnace, 50 percent of the energy at the focal plane is delivered within a circle about 28 cm in diameter (1.6 solar image diameters) (Ref. 4); it is estimated that the laboratory-scale solar furnace delivers 50 percent of its energy within a circle about 2.5 cm in diameter (about 4 solar image diameters). Making the rather gross assumptions that the reflectivities of the heliostats and concentrators are similar, that the insolation values and cosine losses are similar, etc., the maximum fluxes available on the two facilities should be related by the relative areas over which the images are spread:

$$\begin{aligned}\frac{Q}{A}_{\text{lab}} &= \frac{Q}{A}_{\text{CNRS}} \left[\frac{\text{number of image diameters for CNRS}}{\text{number of image diameters for lab}} \right]^2 \\ &= 1,600 \text{ W/cm}^2 \left[\frac{1.6}{4.0} \right]^2 = 256 \text{ W/cm}^2\end{aligned}$$

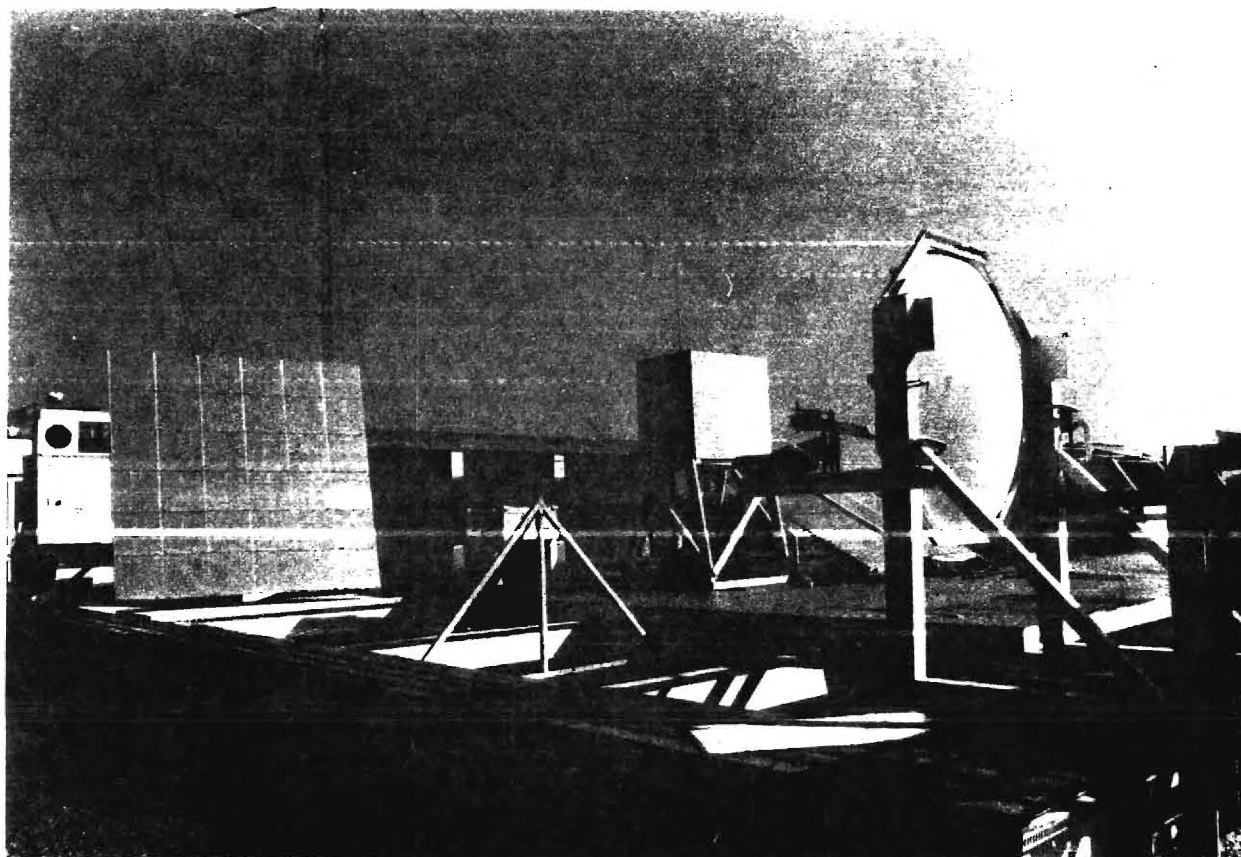
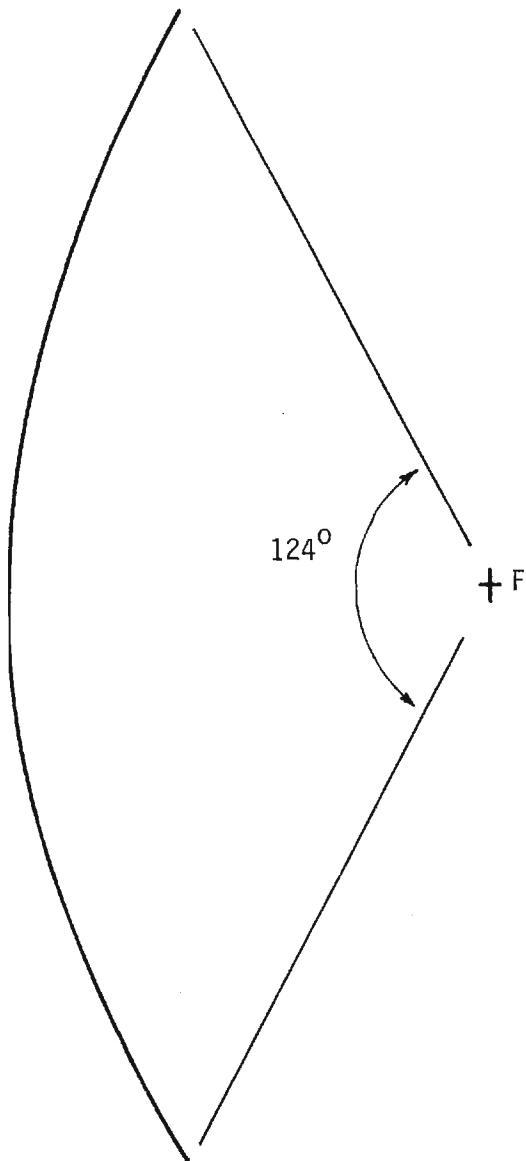


Figure 10. Photograph of laboratory-scale solar furnace on Georgia Tech campus.



Diameter = 152 cm (60 in.)

Focal Length = 63.5 cm (25 in.)

Theoretical Solar Image Diameter =
 $2 f \tan 16' = 0.59 \text{ cm (0.23 in.)}$

Thermal Power at Focal Point =
approximately 1.3 kW

Figure 11. Configuration of paraboloid dish concentrator on laboratory-scale solar furnace.

This value is, in fact, approximately the maximum flux measured on the laboratory solar furnace.

The laboratory solar furnace was judged to be adequate for evaluation of scale model hardware on this program for these reasons:

- (1) Its rim angle is reasonably close to the rim angle at CNRS.
- (2) Its maximum flux is in the same order of magnitude as CNRS.
- (3) It is readily available and inexpensive to use for scale model tests.

Heat flux measurements were made using Gardon-type calorimeters (Ref. 6). These were water-cooled so that they could survive prolonged exposure at the focus of the solar furnace. The calorimeters were purchased from Hy-Cal Engineering of Santa Fe Springs, California and calibrations were furnished by the manufacturer. A photograph of one calorimeter is shown in Figure 12; the active area is 3 mm in diameter.

DOUBLE REFLECTOR FLUX TURNING DEVICE

The overall experimental objective of this program was to devise a method for turning and collimating a beam of concentrated solar radiation. The original beam is strongly converging and arrives along a horizontal axis. It is obvious that the radiant energy should experience the smallest possible number of reflections in order to minimize losses of flux intensity. One concept which appeared attractive was the double reflector scheme, shown schematically in Figure 13, because any given beam should be reflected from only two surfaces. A small secondary parabola is positioned so that its axis and focus coincide with those of the main parabola. A collimated beam will then emerge from the secondary parabola, as shown in Figure 13, and the high-flux collimated beam can be turned to the required final direction by a flat mirror. Two conditions must be met for these relationships to hold exactly:

- (1) The sun must be a point source of light.
- (2) The mirrors must have theoretically perfect shapes and dimensions.

The question to be addressed in investigating this concept was whether the above conditions could be closely enough approximated in practice to yield output fluxes suitable for soil blowoff tests.

The apparatus shown in Figure 14 was constructed to test the double reflecting device concept. The position of the secondary parabola was adjustable with respect to the flat mirror. The collimating tubes visible in Figure 14 were not initially used. Early trials with small paraboloid mirrors revealed that the finite diameter of the solar image from the main parabola caused beam spreading which might be corrected by adopting a spheroid shape for the small mirror. This modification gave promising results when very short working distances were used between the small curved mirror and the flat mirror, but at the expense of substantial shading of the small curved mirror by the flat mirror. The collimating tubes shown in Figure 14, which were Pyrex tubes coated internally with aluminum reflecting films, were added to reduce beam spread and permit longer working distances. Losses in the collimating tubes, however, reduced the output flux to levels which were no longer useful.

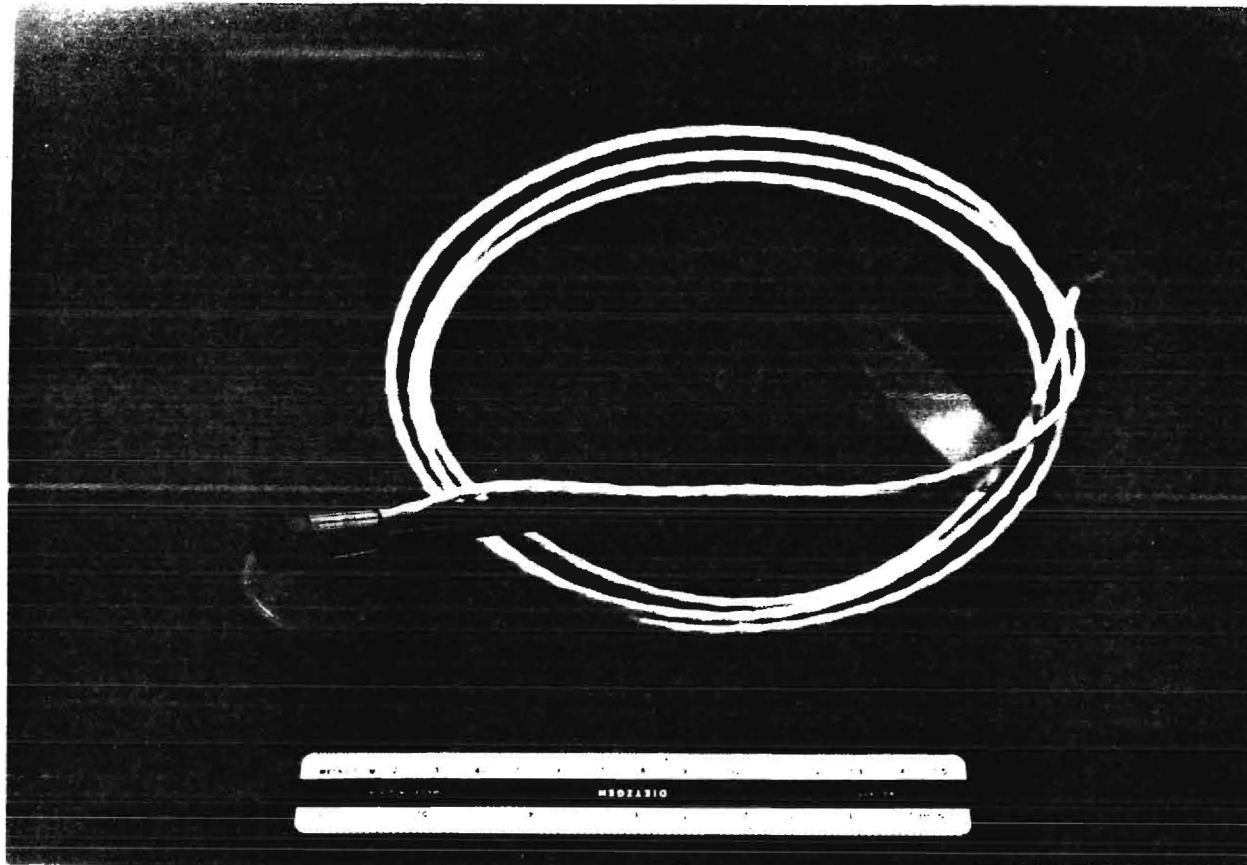


Figure 12. Water-cooled Gardon-type calorimeter manufactured by Hy-Cal Engineering, Santa Fe Springs, California.

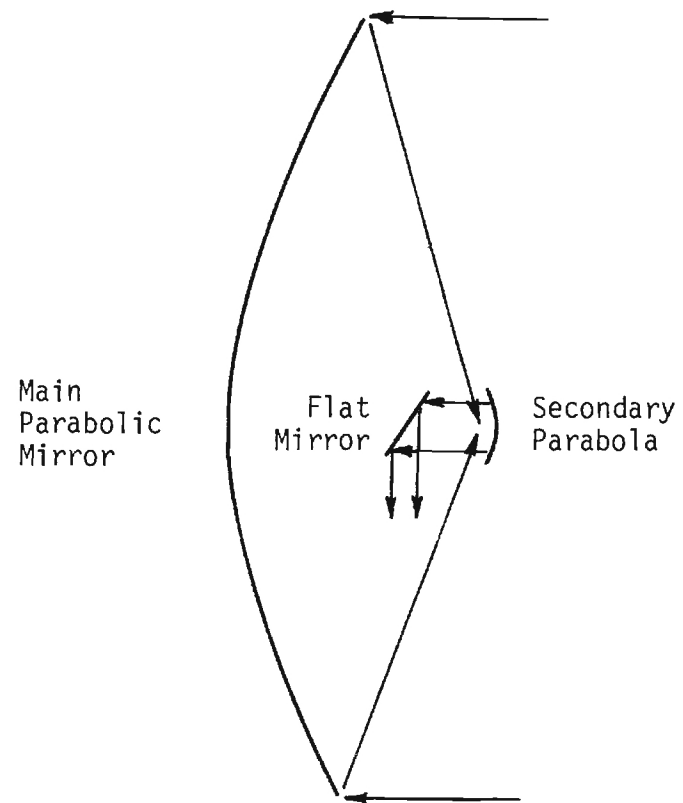


Figure 13. Schematic diagram showing double reflector flux turning concept.

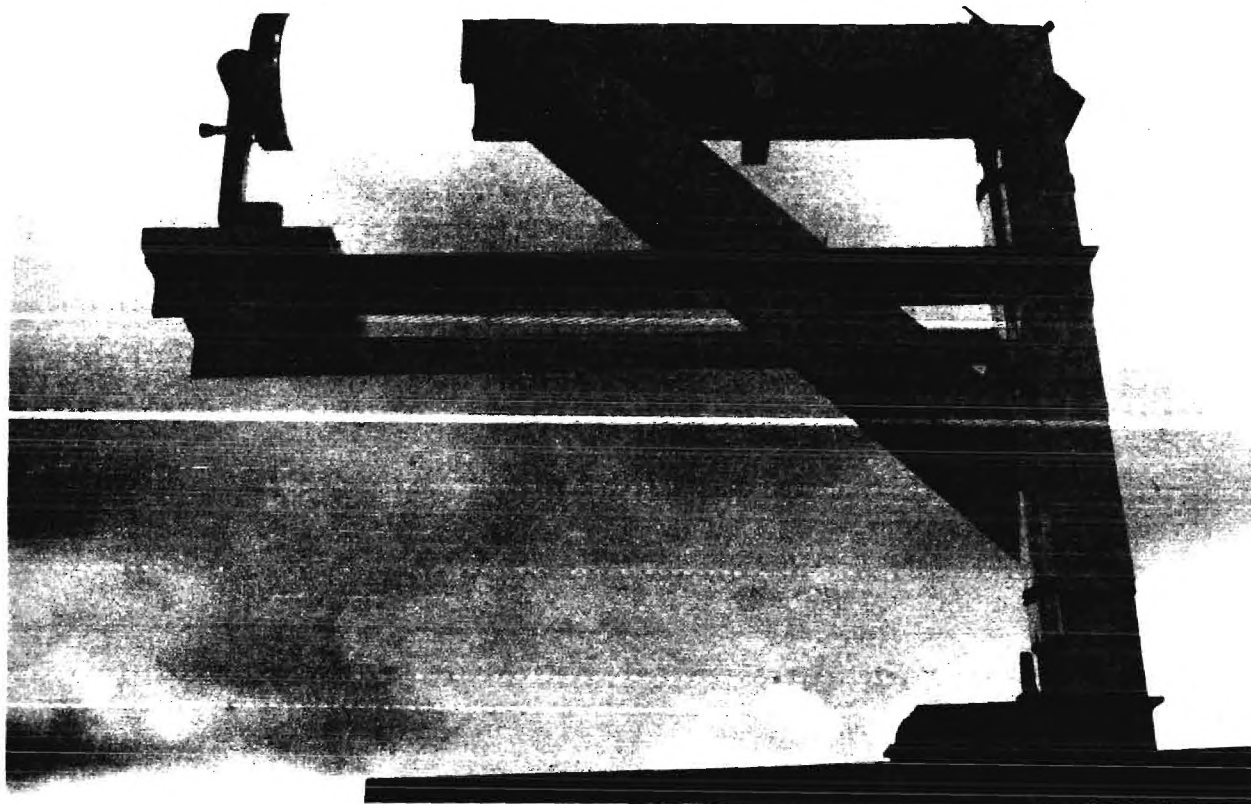


Figure 14. Double reflector flux turning device test apparatus.

The double reflector flux turning device was finally abandoned as a candidate concept for the following reasons:

- (1) The theoretical solar image diameter of the main parabola represents an area receiving approximately the desired level of energy flux. The final output beam must be about this diameter, and certainly not more than a factor of two larger, if useable output fluxes are to be obtained.
- (2) If the output beam is to be similar in size to the main parabola's theoretical solar image size, then the small parabolic mirror must have an active area approximating these same dimensions. The finite-diameter solar image will thus be spread over most of the surface of the small curved mirror, resulting in poor collimation of its output beam.
- (3) The poorly collimated beam from the small curved mirror can be corrected by (a) very short working distances at the expense of shadowing, or (b) collimating tubes at the expense of prohibitively high reflection losses. Neither of these approaches yields useable output fluxes.

LIGHT PIPE DESIGNS

Preliminary consideration of optical hardware suitable for turning the flux at the CNRS Solar Furnace and providing the enclosed column for the atmosphere above the specimen led to the conclusion that hollow light pipes with internally reflecting walls should receive primary consideration. It is desirable that the light pipe configuration allow for disassembly, so that the walls might be cleaned and polished, and that the column above the soil specimen be square or circular in cross section, so that analytical modeling will be facilitated.

Approximately ten light pipe configurations were inspected by manual ray tracing techniques to identify promising candidates for further analysis. Four of these are described in Figure 15 and Table 1. As these designs evolved, all using approximately square cross sections, it became clear that utilization of the radiant energy arriving from wide angles near the horizontal direction would be improved by adopting a semi-circular cross section for the light pipe (Note the angles shown in Figure 4).

The optical configuration shown in Figure 16 was selected to serve as a basic light redirecting structure. This device is composed of three concentric conic sections which receive radiation through an aperture and turn it generally in a downward position. If the solar image at the aperture were a point, rather than having a finite diameter, one could design a curved surface dome for this flux turner from which each reflected ray emerged in the desired direction. The sun's finite diameter, however, prohibits this in the real case. Since a reflector consisting of multiple conic sections is much easier to construct than a continuously curved dome, especially in large sizes, the conic geometry was adopted as being substantially as good as a dome in the real case. The dimensions of the conic sections were selected by manual trials to reflect a large fraction of the rays downward toward the specimen. The aperture diameter was chosen to be about two solar image diameters, which at CNRS would capture about 60 percent of the incident power.

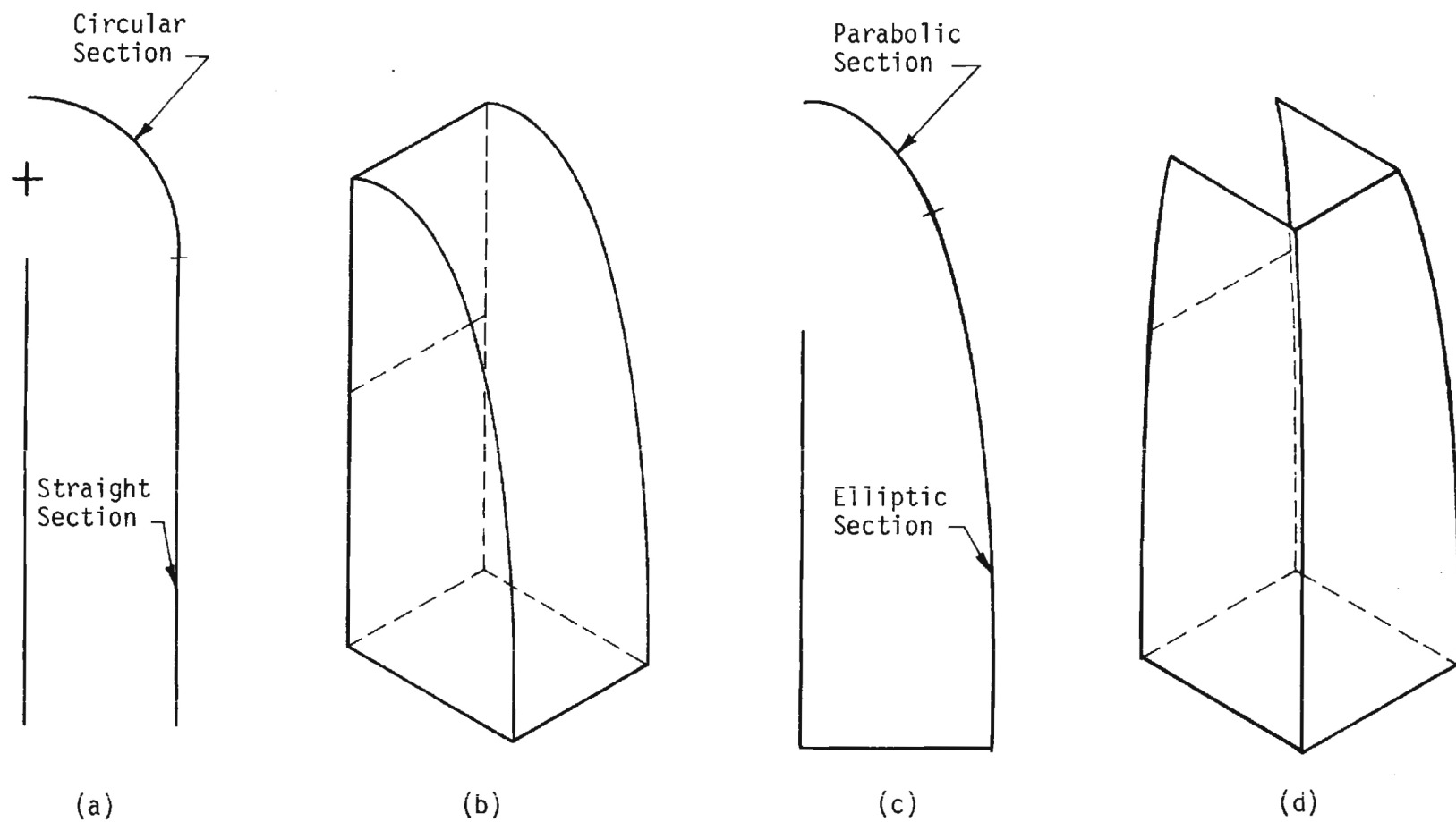


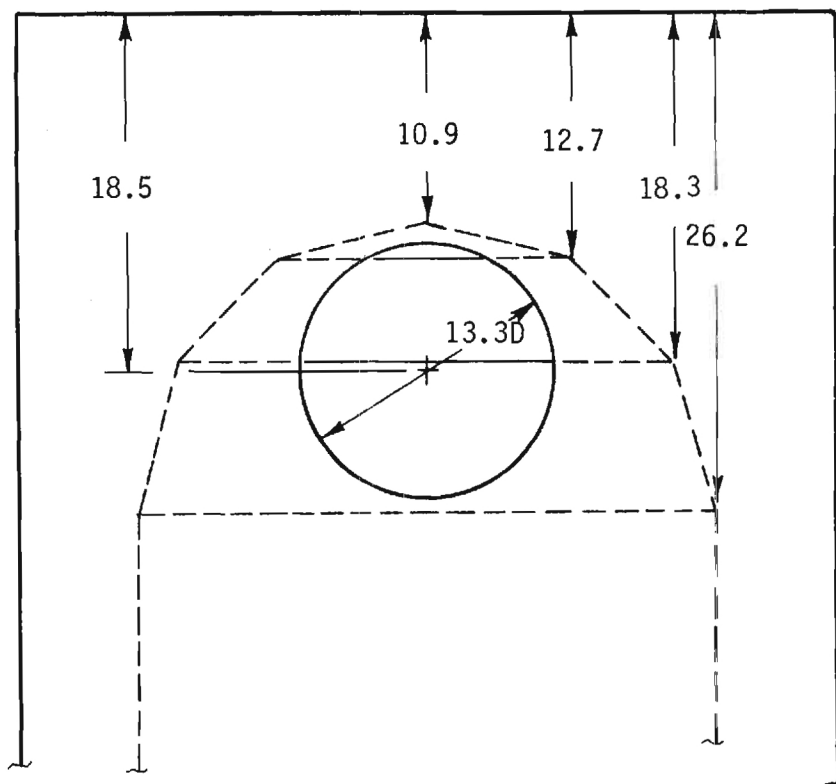
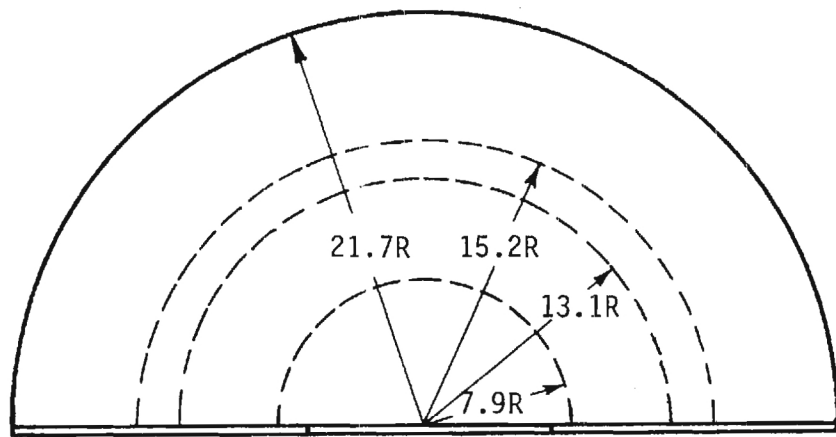
Figure 15. Four candidate light pipe configurations for soil blowoff tests.

Table 1. Data for candidate light pipes.

Sketch Shown in Figure 15	Description	Remarks
(a)	Cylindrical-straight rear wall and flat sides (two-dimensional sketch)	Large fraction of entering light is reflected back through aperture
(b)	Parabolic-cylindrical rear wall and flat sides (three-dimensional sketch)	Average 3.5 bounces per ray for point-source sun; sample plane too large
(c)	Parabolic-elliptic rear wall and flat sides (two-dimensional sketch)	Hot spot on sample plane
(d)	Three parabolic cylindrical walls and open top (three-dimensional sketch)	Very difficult to construct.

Below the domed light-turning structure, a column was constructed to funnel radiation onto the specimen and to confine the atmosphere above the specimen. Two models of this light pipe configuration were built for testing in the laboratory solar furnace. The models were scaled to the furnace's solar image diameter of 0.59 cm (0.23 in.); they are shown in Figures 17 and 18. One has a straight cylindrical pipe section downstream of the domed structure and the other has a cone-shaped section whose outlet aperture area matches the inlet aperture area in the front plate. All reflecting surfaces were carefully polished to remove tool and abrasive marks as completely as possible. Aluminum reflecting surfaces were then applied by vacuum evaporation.

A full scale light pipe for use at the CNRS Solar Furnace would be constructed using a substrate metal, probably copper, coated by another metal to obtain high optical reflectivities on the interior surfaces. The candidate reflecting materials are listed in Table 2. Silver and Beral have the highest reflectivities. Freshly deposited aluminum also has a high reflectivity, but this deteriorates rapidly as an oxide coating is formed; aluminum may be protected by an evaporated silicon monoxide film but the reflectivity of the coated aluminum surface is about the same as that of an aged surface. From the data in Table 2, it can be seen that silver is the material of choice for two reasons: (1) the highest possible reflectivity is needed to minimize flux losses caused by multiple bounces of light rays in the pipe, and (2) the short exposure times and rather dirty nature of the experiments imply that periodic cleaning of the reflecting surface will be necessary, that the fragile nature of Beral or aluminum films are incompatible with cleaning, but that electroplated silver is capable of being cleaned and



dimensions in millimeters

Figure 16. Basic light redirecting structure consisting of conical segments.

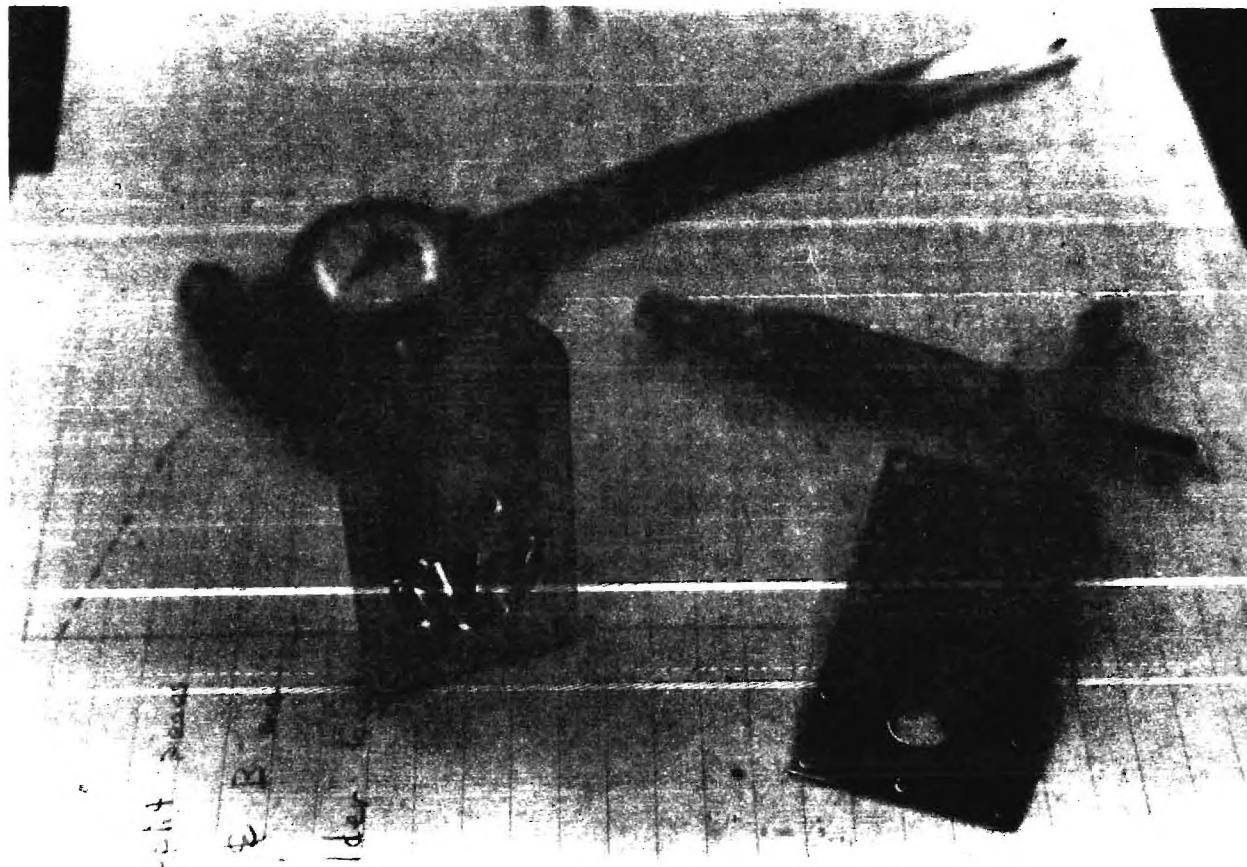


Figure 17. Straight sided light pipe model during fabrication.

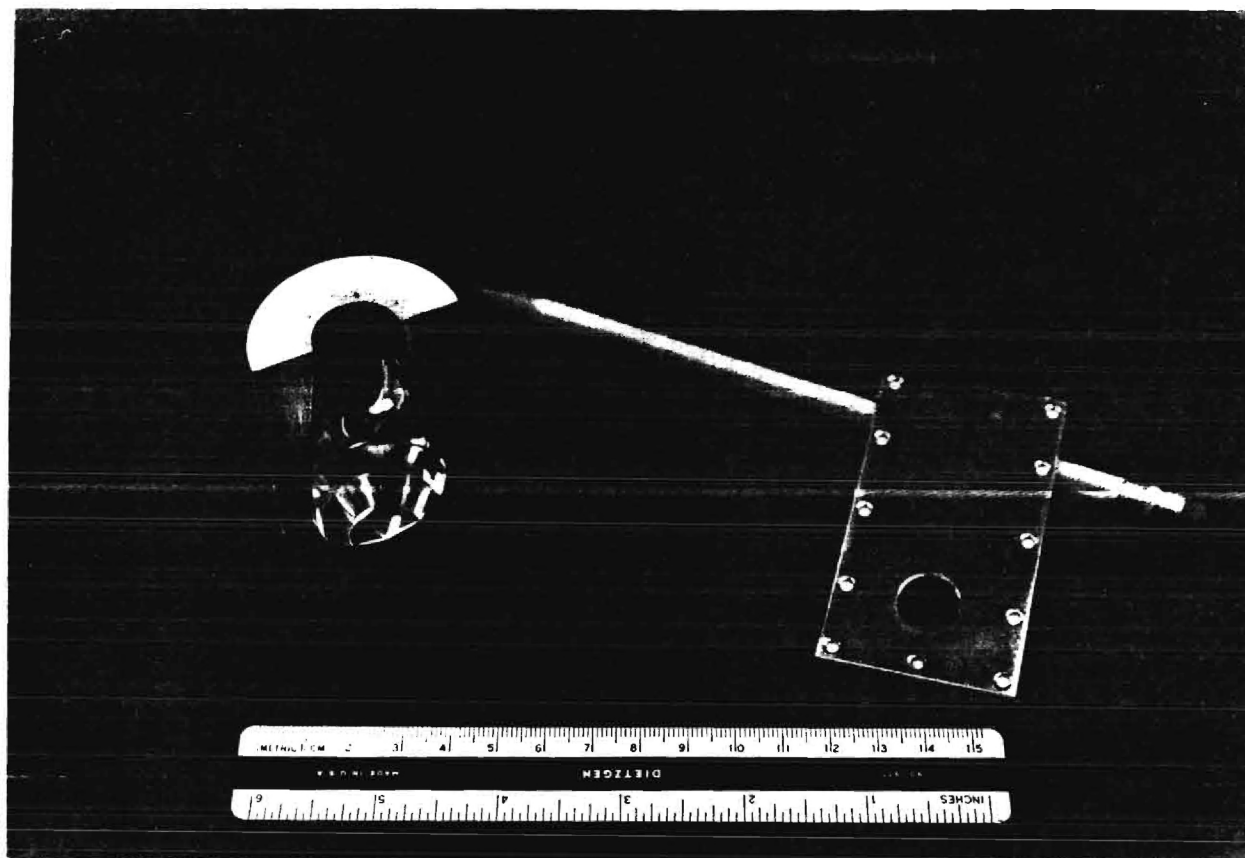


Figure 18. Funnel shaped light pipe model after application of reflecting surface.

Table 2. Reflectivities of mirror materials.

Material	Reflectivity over Visible Spectrum (percent)	Remarks
Silver	90-95 ^a 90-95 ^b	Tarnishes on exposure to atmosphere
Aluminum	75-85 ^a 75-85 ^c	Must be deposited by vacuum evaporation; reflectivity deteriorates if not protected by overcoat
Beral (aluminum-beryllium alloy)	85-88 ^c	Must be deposited by vacuum evaporation; proprietary alloy available from only one source ^e
Rhodium	78-80 ^b 85-87 ^d	Must be deposited by vacuum sputtering; excellent weathering qualities
Chromium	70-75 ^d	Reflectivity deteriorates slowly after exposure to atmosphere
Nickel	70-75 ^d	Reflectivity deteriorates rapidly after exposure to atmosphere; makes good base for evaporated surfaces

NOTES: a. Ref. 7
b. Ref. 8
c. Ref. 9
d. Ref. 10
e. Beral evaporated coatings are manufactured by the Dudley LeRoy Clausing Company of Skokie, Illinois.

polished. The model light pipes were coated with aluminum because this could readily be done on campus without delays associated with issuing a purchase order for commercial plating.

LIGHT PIPE TESTS

The two model light pipes shown in Figures 17 and 18 were tested in the laboratory solar furnace at Georgia Tech; photographs of the experimental apparatus are shown in Figures 19 and 20. The light pipe was supported on a sliding fixture which could be moved perpendicular to the axis of the parabolic dish, placing in the focus either the light pipe's aperture or an "input" calorimeter. An "output" calorimeter was mounted at the light pipe's exit plane. The test pipe was placed in an inverted orientation for experimental convenience, but this did not affect experimental results since the furnace is symmetric about its horizontal axis (the parabola is not truncated as at CNRS).

Results of the experimental measurements are shown in Table 3. The flux values given in the table are averages of five repeated runs in which inlet and outlet fluxes were determined successively. When these were multiplied by the respective inlet and outlet apertures, energy balances could be made for analytical treatment of alternate designs and surface reflectivities. A set of experiments to measure flux distribution over the aperture of one light pipe gave values consistent within about ± 10 percent for the measurement positions selected. The experimental data clearly show that the cylindrical column configuration has smaller optical losses than the cone; it is preferred for this reason as well as because a column of uniform cross section will facilitate analysis of soil blowoff data. The cone-shaped column proved, however, that higher fluxes could be obtained by throttling the output beam. It was impractical to construct a smaller domed reflecting structure because of fabrication and polishing considerations.

LIGHT PIPE ANALYSES

Using the experimental data from the two light pipe models tested on the laboratory solar furnace, it is possible to estimate the output fluxes which might be expected from alternate configurations and surface reflectivities. This extrapolation is based principally on the fact that the energy remaining in a reflected ray after several reflections is

$$F = R^n \text{ or } \log F = n \log R$$

where F = fraction of energy remaining in the beam

R = "gray body" reflectivity of the reflecting surface

n = the number of reflections

In order to model the performance of a light pipe, one must run an energy balance which adequately accounts for all reflective losses. A computer analytical model existing at Georgia Tech was adapted to the light pipe problem. The most important conclusion derived from this model was the fact that approximately 3.0 percent of the incoming rays at the light pipe aperture either missed the aperture or were reflected back through it; of the remaining rays, 96.4 percent emerged at

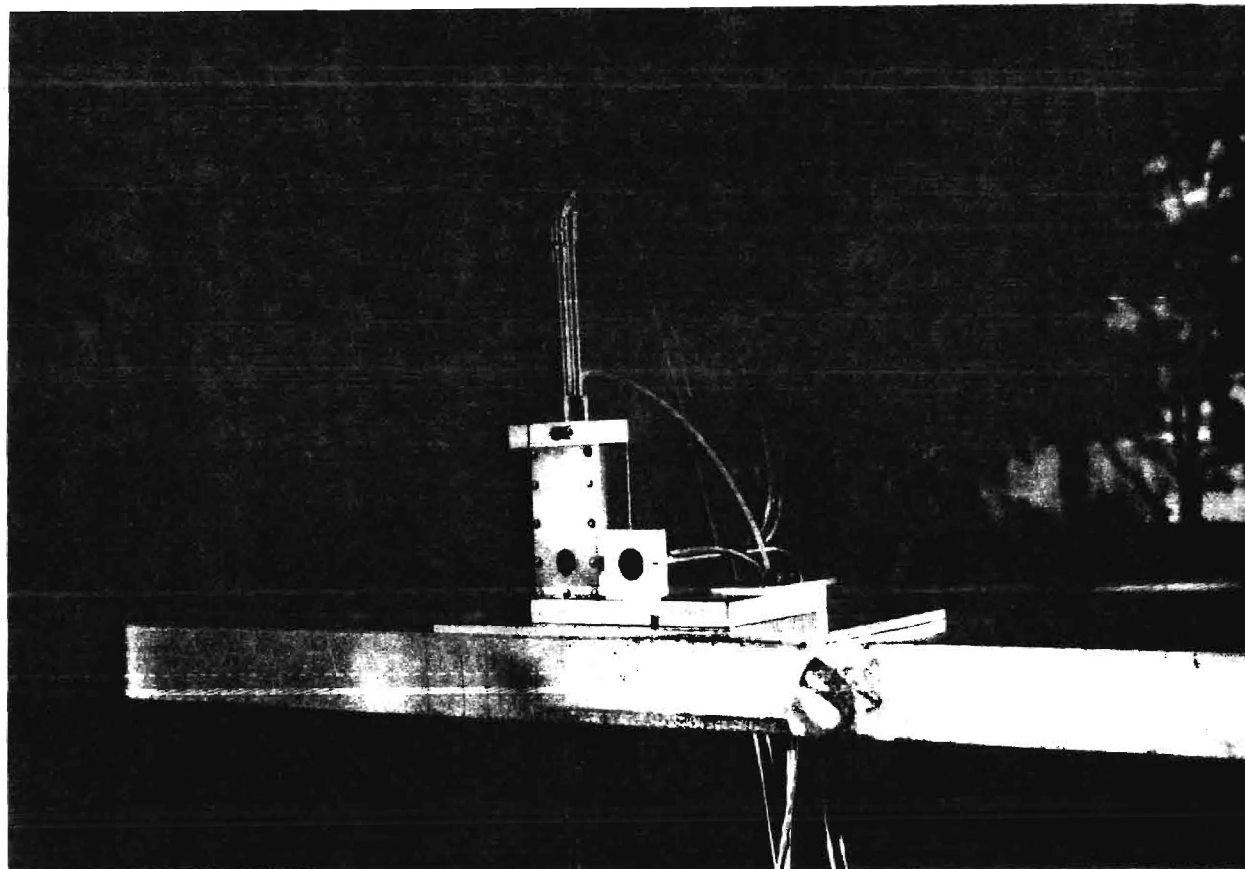


Figure 19. Experimental light pipe and calorimeter assembly.

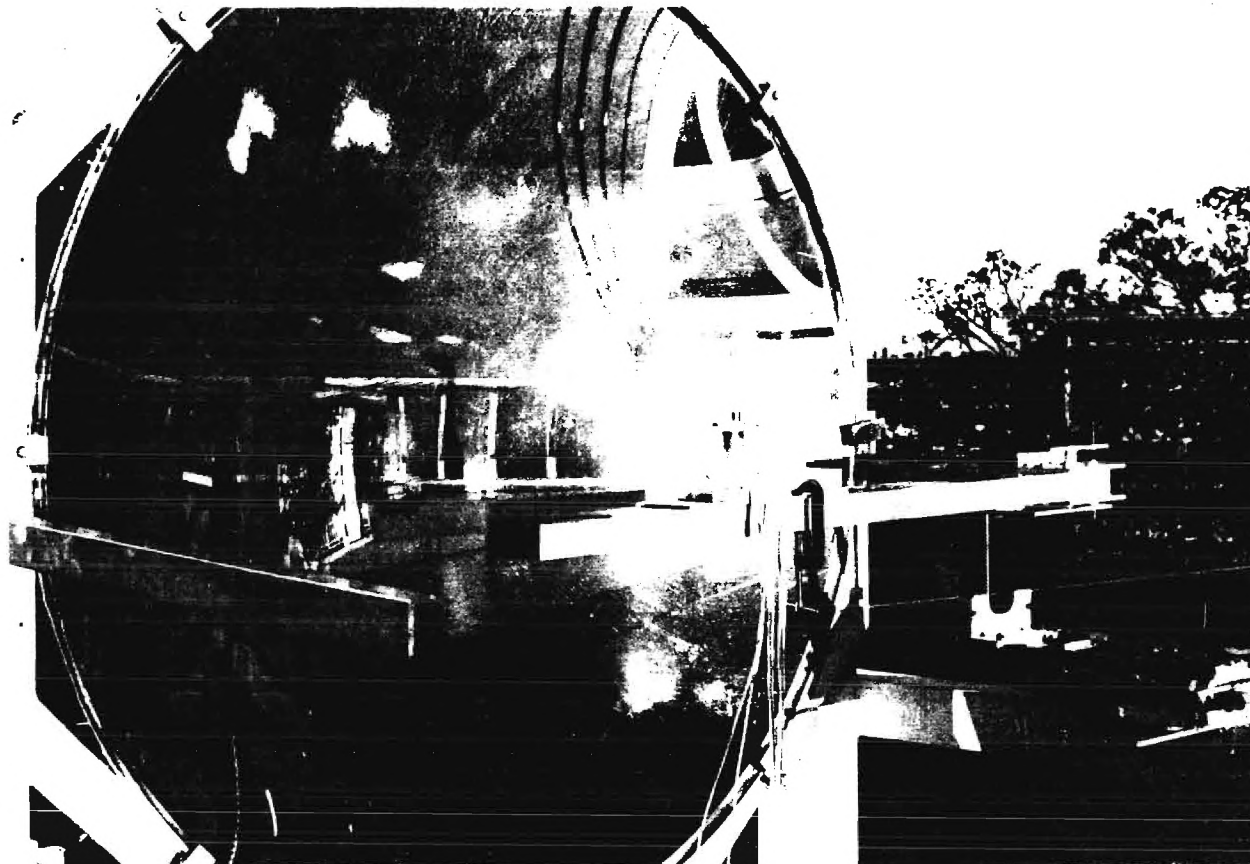


Figure 20. Parabola and light pipe assembly while test is underway.

Table 3. Experimental results of light pipe tests.

Parameter	Cylindrical Column Light Pipe (Figure 17)	Conical Column Light Pipe (Figure 18)
Flux over inlet aperture ($\text{cal}/\text{cm}^2\text{s}$)	62.9	39.6
Inlet aperture area (cm^2)	1.394	1.394
Energy crossing inlet aperture (cal/s)	87.7	55.2
Flux over outlet aperture ($\text{cal}/\text{cm}^2\text{s}$)	8.14	8.68
Outlet aperture area (cm^2)	3.645	1.239
Energy crossing outlet aperture (cal/s)	29.7	10.8
Fraction of energy transmitted (percent)	33.9	19.6

NOTES: Aluminum reflecting surfaces; reflectivity 75-85 percent.

Variation in inlet aperture flux was caused by different insolation values on the days tests were conducted.

the exit plane and 0.6 percent were unaccounted for. Since conservation of rays was not obtained in the computer model, it was used only to estimate the net fraction of energy lost through "back reflection."

The remaining analysis of the two light pipe models is traced in Table 4. From the data shown in the last three lines of the table, it is reasonable to expect that fluxes at the sample plane ranging from one-third to two-thirds of the values at the inlet aperture plane can be obtained under the following design conditions:

- (1) The light pipe should have the cylindrical column configuration shown in Figure 17 except that the inlet aperture must be larger with respect to the remainder of the structure; the dimensions of the dome must be adjusted to accommodate the larger inlet aperture.
- (2) For use at the CNRS 1000 kW Solar Furnace, the light pipe inlet aperture should be approximately one solar image diameter (17 cm or 6.7 in.); upon completion of the heliostat realignment program currently being performed by CNRS, this should give an average inlet flux of at least $294 \text{ cal/cm}^2\text{s}$ and an inlet power of at least 270 kW.
- (3) The semi-circular outlet aperture of the light pipe should be equal in area to the inlet aperture (radius of 12 cm or 4.75 in.).
- (4) The light pipe structure should be machined from copper or brass, polished to a high luster with all tool marks removed, electroplated with silver, and polished to a high specular reflectivity.

A preliminary heat conduction analysis has been conducted to evaluate the danger of melting the surface of a light pipe exposed to the peak incident flux at the CNRS Solar Furnace ($383 \text{ cal/cm}^2\text{s}$). This suggests that the light pipe structure should be fabricated with walls on the order of 1 to 2 cm thick but that water cooling should not be necessary for exposure times up to about 10 seconds. Machined copper disks withstood incident fluences of 1,100 to 1,200 cal/cm^2 during exposures to incident fluxes of about $300 \text{ cal/cm}^2\text{s}$ at the CNRS facility (Ref. 11). The higher reflectivity of a polished, silver-plated surface should permit larger fluences to be accepted, provided the silver remains bright.

Table 4. Analysis of light pipe experiments.

Parameter	Cylindrical Column Light Pipe (Figure 17)	Conical Column Light Pipe (Figure 18)
Energy crossing inlet aperture from Table 3 (cal/s)	87.7	55.2
Net energy into light pipe (0.964 x energy crossing inlet aperture) (cal/s)	84.5	53.2
Energy crossing outlet aperture from Table 3 (cal/s)	29.7	10.8
Fraction of net energy transmitted	0.351	0.203
Reflectivity of aluminum surface from Table 2	0.80	0.80
Average number of reflections for each ray ($n = \log F / \log R$)	4.69	7.15
Reflectivity of silver surface from Table 2	0.92	0.92
Fraction of net energy recoverable with silver surface ($F = R^n$)	0.676	0.551
Maximum fraction of energy recover- able assuming $R_{A1} = 0.75$ and $R_{Ag} =$ 0.95	0.830	0.753
Minimum fraction of energy recover- able assuming $R_{A1} = 0.85$ and $R_{Ag} =$ 0.90	0.507	0.356

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been reached on this research program:

- (1) It is feasible to perform tests for irradiation of soil specimens at the CNRS 1000 kW Solar Furnace. Fluxes incident on the sample plane can be expected to fall within the range of one-third to two-thirds of the values incident at the focal plane of the facility (100 to 200 cal/cm²s at the sample plane). These flux values are sufficiently high to model a significant portion of DNA's desired test range (see Figure 1).
- (2) The fluxes incident at the focal plane of the CNRS 1000 kW Solar Furnace can be turned by hollow light pipes using silver reflecting surfaces on the interior walls. From the viewpoint of optimum light pipe geometry, the vertical column above the sample plane should have a semi-circular cross section of constant area. If this geometry is too great a deviation from the preferred circular or square cross sections, the preferred cross sections might be provided with some sacrifice in flux at the sample plane.
- (3) Vertical slit windows and other measurement devices can be incorporated into the light pipes without significant degradation of optical performance but with increases in equipment complexity. For the first experiments at CNRS, existing automatically timed shutters can be used; these furnish a pulse shape approximately square with respect to time (opening time about 0.1 to 0.2 seconds and closing time about 0.2 to 0.3 seconds).
- (4) Light pipe designs are constrained by the requirement that the inlet and outlet apertures be approximately equal in area; otherwise the optical losses significantly degrade the flux available at the sample plane.
- (5) The double reflector flux turning device, employing a curved redirecting mirror near the focus of the large parabolic mirror, is not feasible for reasons given in this report.
- (6) Fluxes higher than those available at the sample plane of "right angle" light pipes developed on this program may be obtainable if some compromise in experimental test conditions can be permitted; for example, orientation of specimens in a sloping, rather than horizontal, position or the use of tapered light pipes with non-constant cross section.

The engineer in charge of the CNRS 1000 kW Solar Furnace has indicated his willingness to collaborate on soil measurement programs under DNA sponsorship, provided however, that the experimental details and participating personnel must be approved by CNRS prior to initiation of work. It appears that the next step toward performing the required measurements is the testing of a full-scale light pipe at the CNRS facility. Accordingly, Georgia Tech makes the following recommendations:

- (1) Small coupons of light pipe wall structures should be tested at the CNRS Solar Furnace in mid-1979. The coupons would be silver-plated copper and silver-plated brass having diameters of about 5 cm (2 in.) and thicknesses of 1 to 2 cm ($\frac{1}{2}$ to 1 in.). The purpose of the tests would be to assure that the reflecting surfaces will survive exposures to the anticipated incident fluences under actual test operating conditions; incident fluxes should be the highest levels available (about 400 cal/cm²s) and fluences should correspond to exposure times up to about 10 seconds (4,000 cal/cm²). These tests could be conducted during a planned trip to the CNRS Solar Furnace for another research program in April 1979. If it were found that the candidate wall structures could not survive these exposure conditions, then provisions for forced cooling of light pipes would be required.
- (2) During the same trip to the CNRS Solar Furnace, detailed agreements for subsequent test campaigns should be worked out. Since diagnostic techniques for soil blowoff measurements have already been developed by Science Applications, Incorporated, it would be extremely helpful to the Defense Nuclear Agency program if CNRS would permit one representative of SAI to accompany Georgia Tech personnel on subsequent test campaigns; the tests might be conducted under the direction of CNRS and Georgia Tech, with the SAI representative assisting in the area of diagnostic instrumentation.
- (3) Detailed design and construction of a full-scale light pipe for soil tests should be performed. It is presently recommended that the light pipe follow the design conditions given on page 35 of this report, that cooling be accomplished by providing sufficient heat capacity in the walls (sufficient wall thickness) to accept exposures up to about 10 seconds, and that provisions be made for windows, thermocouples, guillotine shutters and other diagnostic equipment as appropriate. Design details of these accessories will be coordinated with SAI under the direction of DNA.
- (4) The full-scale light pipe should be subjected to proof testing at the DOE Advanced Components Test Facility at Georgia Tech in order to demonstrate that it can survive incident fluences chosen to simulate the reflective surface temperatures which will be attained at the CNRS Solar Furnace, to measure the fraction of the input flux which reaches the specimen plane, and to permit development of photographic documentation techniques. Although the flux level and rim angle provided by the ACTF do not match those at CNRS, these tests might prevent mistakes on the first test campaign in France.
- (5) An initial test campaign at the CNRS Solar Furnace should be conducted in late 1979 if the arrangements and light pipe tests are successfully completed. This work, like the coupon tests described above, might be accomplished during a trip which is scheduled for another research program (sharing of travel and other expenses would benefit both programs). In these tests, soil samples would be irradiated and all data collection procedures would be employed. The results of this work would assist in defining the scope of subsequent research and test activities.

- (6) A continued limited-scale effort for development of test and instrumentation techniques should be conducted. Alternate reflector designs for flux turning, very small thermopiles for temperature measurement, particle characterization by infrared television, other ideas which might be useful for soil blowoff measurements have been suggested during the course of this research program. A limited investment in further exploration of these subjects might ultimately yield useful testing capability, although these activities must not impede the basic goal of conducting soil tests in late 1979.

SECTION IV

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DNA _____

TECHNIQUES FOR INVESTIGATING MATERIALS
IN A RADIANT HEAT ENVIRONMENT

Georgia Institute of Technology
Engineering Experiment Station
Atlanta, Georgia 30332

31 August 1981

Final Report

CONTRACT NO. DNA 001-78-C-0261

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SUMMARY

The long range objective of this program is to measure quantitatively the behavior of soil specimens while they are subjected to simulated thermal pulses from nuclear weapons. This report describes participation by the Georgia Institute of Technology in a series of test programs for the Defense Nuclear Agency to meet the above objective. Georgia Tech, Science Applications, Incorporated, and the University of Denver Research Institute conducted measurement programs during 1979 and 1980 at the CNRS 1000 kW Solar Furnace in France to acquire data on the behavior of soils under simulated thermal pulses.

SECTION I

INTRODUCTION

Prediction of the effects of nuclear weapons is of interest to the Defense Nuclear Agency (DNA) for assessment of the probable damage to targets under various military scenarios. In order to perform these predictions by analytical methods, it is necessary that certain transport properties of the media surrounding the point of detonation be known. In this investigation, the transport properties of the atmosphere near the surface of the ground were of interest.

Under certain combinations of soil type and radiant thermal fluxes from the fireball, it is possible for soil materials, such as particles, water vapor, and smoke from burning vegetation, to be ejected into the atmosphere above the soil surface. If this occurs, the transport properties of the atmosphere are altered and the shock wave, arriving a few seconds after the thermal pulse, behaves differently than if it were traveling through undisturbed air. In order to perform analytical modeling of the shock wave propagation, the transport properties of the atmosphere must be known or estimated. The purpose of this program was to acquire such information by an experimental method.

Solar furnaces provide high radiant heat fluxes with spectral distributions reasonably approximating those emitted by nuclear weapon fireballs. The Centre National de la Recherche Scientifique (CNRS) 1000 kW Solar Furnace at Odeillo, France has the most suitable characteristics of any such facility in the world for simulating the effects of nuclear weapon fireballs on soils: a very high incident flux at the focus (about $1,200 \text{ w/cm}^2$) and a high enough power level to illuminate relatively large specimens (about 1 MW of thermal power).

Science Applications, Incorporated (SAI) and the Georgia Institute of Technology (GIT) have worked cooperatively under separate contracts from DNA to carry out a research program for evaluation of soil specimens exposed to simulated nuclear weapon thermal pulses. This report describes work performed by GIT during the period March 1979 through December 1980 under contract DNA001-78-C-0261.

RESPONSIBILITIES OF THE GEORGIA INSTITUTE OF TECHNOLOGY

GIT was responsible for certain clearly defined activities under this cooperative research program for DNA:

- (1) To serve as DNA's liaison with CNRS, including coordination with CNRS personnel on test schedules, test plans, and related matters.
- (2) To perform coordination between CNRS and the numerous DNA contractors who were active on the program at various times, including SAI, the University of Denver Research Institute (DRI), and others.
- (3) To make payments to CNRS, through GIT's Research Services Agreement with CNRS, for solar furnace charges, professional services of CNRS personnel, and reimbursement of freight expenses.
- (4) To attend program meetings and participate in the planning of test programs and the review of test results.

- (5) To conduct proof testing of the SAI diverter and light pipe assembly during July 1979, prior to the first test program at the CNRS Solar Furnace.
- (6) To procure and transport assigned equipment and supplies for test programs at the CNRS Solar Furnace in August 1979, February-March 1980, and September 1980.
- (7) To furnish two engineers at the CNRS Solar Furnace during the three test programs, for operation of photographic equipment, work coordination, and assisting in the setup and operation of test equipment.
- (8) To make all photographic records of the tests (excluding the light transmission experiment conducted by DRI in March 1980), handle processing of all color films, distribute photographic records to the team members, and forward black and white films to a DNA office in Albuquerque, New Mexico for processing.
- (9) To prepare and distribute written inputs for test program reports, including descriptive materials and logs of the photographic films.

TEST REQUIREMENTS

The incident beam at the CNRS 1000 kW Solar Furnace arrives at the focus from an approximately horizontal direction. DNA and its contractors defined the following test requirements for the soil evaluation tests at that facility:

- (1) The soil sample should lie in a horizontal plane with the incident radiation arriving downward from a direction approximately normal to the sample plane.
- (2) The atmosphere above the soil should be surrounded by a column with reflecting walls so that the atmosphere appears to be an infinite medium; the height of the column should be two to four meters.
- (3) The linear dimension(s) of the sample should be 15 to 30 cm (6 to 12 inches); a round or square sample configuration is preferred.
- (4) The transport properties of the atmosphere must be determined as functions of time and height above the sample plane, beginning at the time of initiation of the thermal pulse and ending at the time of shock wave arrival for the weapon parameters under consideration.
- (5) The soil behavior must be documented photographically and particle samples should be collected at various heights above the specimen plane.
- (6) The optical system used to turn or otherwise process the beam of concentrated solar radiation arriving at the focal zone of the solar furnace must cause a minimum attenuation of the incident flux.

In order to conform to the test requirements, SAI designed and constructed a water-cooled light pipe with a curved section at the top to turn the incident focused solar radiation along the axis of the pipe. The light pipe was mounted

vertically, with the inlet aperture of the curved section (the "diverter") positioned at the focus of the solar furnace. The soil specimen was usually placed in a pan at the bottom of the pipe, lying in a horizontal plane (some runs were conducted with the sample pan supported inside the light pipe rather than at the bottom). Various sampling ports and transparent windows were placed along the length of the light pipe (the "sample chamber") in order to permit samples of the atmosphere to be withdrawn, temperature probes to be inserted, and photographs to be made during the runs.

A preliminary evaluation of candidate materials for the light pipe wall was conducted by GIT at the CNRS Solar Furnace in April 1979, during a test program for another sponsor; these tests provided a basis upon which SAI could select wall materials and reflective coatings. A light pipe assembly was proof tested at the Advanced Components Test Facility (a solar thermal test facility operated by GIT for the Department of Energy and located on the GIT campus) in July 1979; this test gave some assurance that the light pipe would survive exposures in a solar furnace before resources were committed for a trip to France. Three test programs were conducted at the CNRS 1000 kW Solar Furnace in August 1979, February-March 1980, and September 1980; these programs conducted soil exposure experiments and collected data for subsequent analysis. SAI was responsible for the light pipe and experiment design, with input from other members of DNA's project team; GIT's responsibilities have been listed earlier.

SECTION II

EXPERIMENTAL WORK

TESTS OF CANDIDATE WALL MATERIALS

GIT conducted tests of candidate light pipe wall materials at the CNRS 1000 kW Solar Furnace during the period April 18 through May 2, 1979. At that time, a test program was underway on another research contract and the addition of a small number of samples for this DNA program could be accomplished without significant costs, except the costs of the specimen materials. SAI furnished approximately 30 specimens and Georgia Tech furnished 12 specimens. These tests provided a basis for selecting light pipe construction materials.

Weather conditions at the solar furnace during the test period were very poor and only nine specimens were run. The specimens were exposed to the full flux available at the focal point of the facility at the time the tests were conducted. Front surface temperatures were measured by an infrared optical pyrometer, back surface temperatures were measured on some samples by thermocouples, and 16 mm color movies were made on all samples. Essential data, as determined from the movie records, are shown in Table 1. The aluminum reflecting films on three substrates were applied by vacuum evaporation. The silver films on the remaining substrates were electroplated and polished to give the best smoothness and specular reflectance possible; the steel substrates retained some evidence of tool marks.

The movies and the data shown in Table 1 show that silver is superior to aluminum as a reflective material for the light pipe walls. Copper seems to be the preferred substrate because its high thermal conductivity causes heat to move away from the surface rapidly; it and brass can also be polished more easily than steel. These tests, on uncooled samples, indicated that the light pipe should be expected to survive irradiation near the focus of the solar furnace.

PROOF TESTING OF THE LIGHT PIPE ASSEMBLY

SAI constructed its proposed light pipe assembly, consisting of a curved, beam-turning section (the diverter) and a four-foot long straight section (the sample chamber) in early 1979. The diverter was built from brass with all surfaces exposed to the solar flux being silver plated and the sample chamber was made from steel with exposed surfaces silver plated. It was generally agreed that a proof test at a solar facility in the U. S. was needed before time and resources were expended to conduct testing at the CNRS Solar Furnace in France. SAI proposed to conduct proof testing at the Central Receiver Test Facility (CRTF), a solar thermal test facility operated by Sandia Laboratories for the Department of Energy in Albuquerque, New Mexico. The CRTF's schedule could not accommodate a test of the SAI device before a test program scheduled at CNRS in August 1979.

It was determined that the proof testing should be conducted at the Advanced Components Test Facility (ACTF), a solar thermal test facility operated by GIT for the Department of Energy. These tests were conducted during the period July 23-28, 1979. Photographs of the ACTF and the light-pipe assembly are shown in Figures 1 and 2.

The objectives of the proof testing were:

Table 1. Solar Furnace measurements of wall materials

Material	Incident flux (cal/cm ² -s)	Maximum fluence (cal/cm ²)	Remarks
Aluminum plated on brass	273	2785	Melting began at 2129 cal/cm ² ; pouring began at 2348 cal/cm ² ; Runn II/35
Aluminum plated on copper	173	2543	No damage at end of test; 2 in. diameter by 1/4 in. thick; Run I/12
Aluminum plated on steel	274	2795	Melting began at 1644 cal/cm ² ; Run II/37
Silver plated on brass	186	2734	No damage at end of test; 2 in. diameter by 1/4 in. thick; Run I/11
Silver plated on copper	192	2803	No damage at end of test; 2 in. diameter by 1/4 in. thick; Run I/10
Silver plated on copper	229	4946	Slight decrease in reflectance after test; 2 in. diameter by 1/4 in. thick; Run I/16
Silver plated on copper	273	4778	Sample melted at end of test; Run II/33
Silver plated on steel	274	4740	Particles ejected at 4274 cal/cm ² ; melting began at 4357 cal/cm ² ; Run II/34
Silver plated on steel	273	5324	Particles ejected at 4750 cal/cm ² ; Melting began at 4859 cal/cm ² ; Run II/36

- (1) To determine whether the cooling water system was adequate to protect the assembly from damage during run times of to ten seconds.
- (2) To measure the flux at the diverter exit and at the sample chamber exit, so that the flux at these planes during tests at the CNRS Solar Furnace could be estimated.

Although the characteristics of the ACTF and the CNRS Solar Furnace do not match very well (the rim angle is 45 degrees at the ACTF versus 74 degrees at CNRS and the power level into a six-inch aperture is about 25 kW at the ACTF versus about

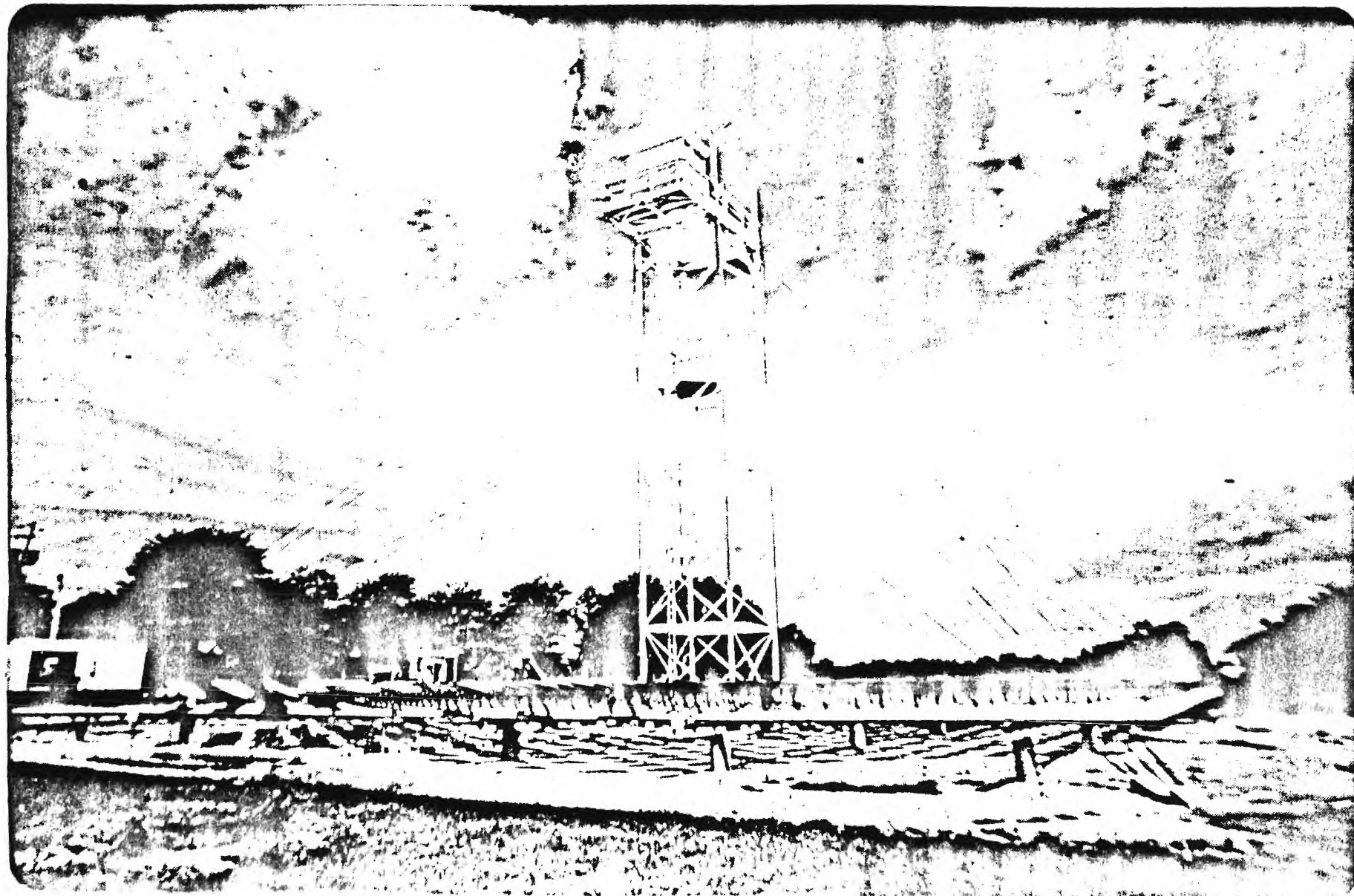


Figure 1. General view of the Advanced Components Test Facility.

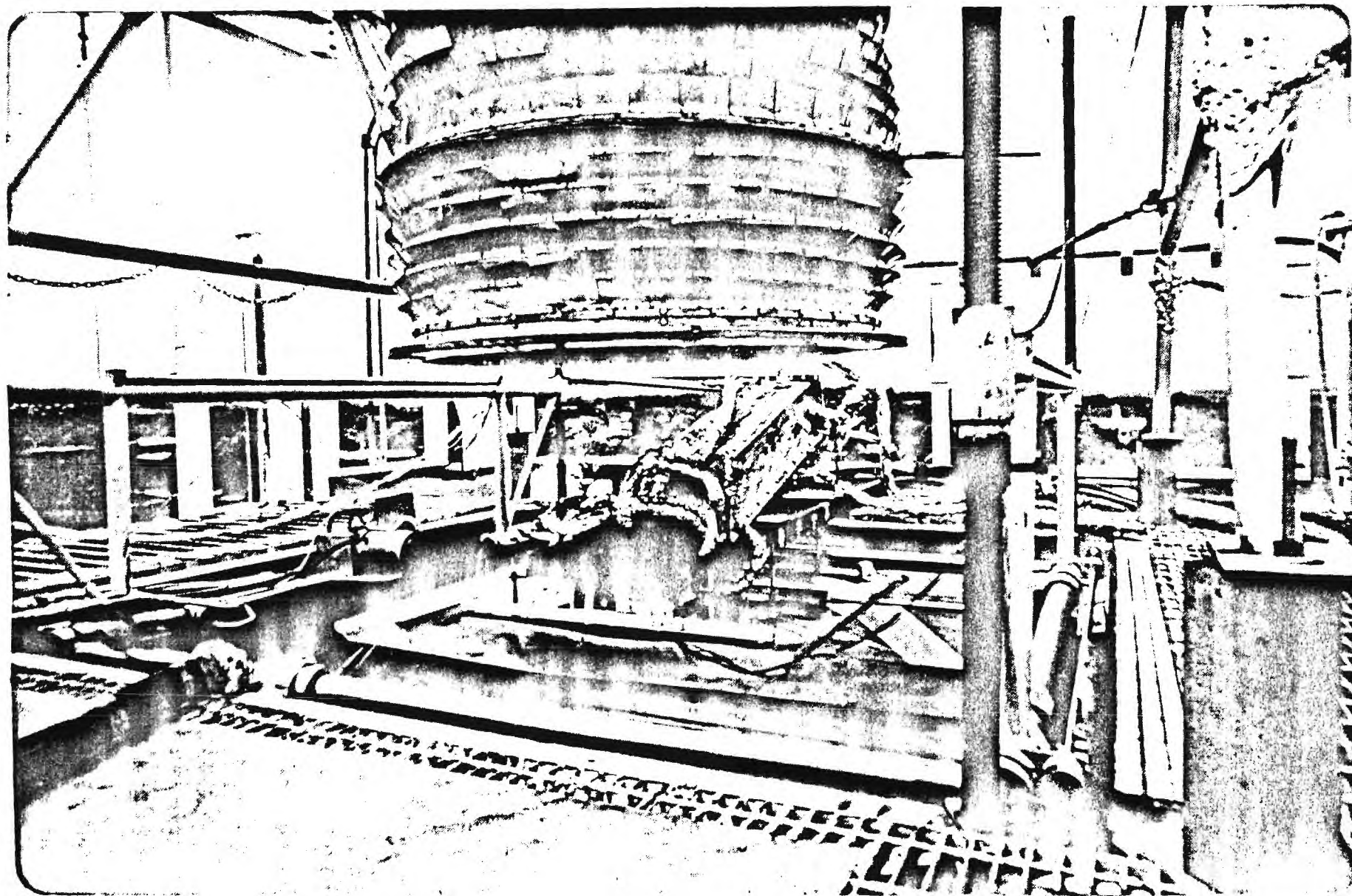


Figure 2. SAI light pipe assembly installed at ACTF for proof testing.

250 kW at CNRS) the high cost of an unproductive trip to France seemed to warrant testing under the conditions available at the ACTF.

A total of 19 runs were made, 24 with the diverter and sample chamber and six with the diverter only. Fluxes at the three measurement planes were measured using eight Hycal calorimeters mounted on an aluminum heat sink plate. Throughput fluxes for a typical run are shown in Table 2; the overall flux throughput of 25 percent was about half the expected value, but if that fraction of the inlet flux were obtained at CNRS, useful measurements could be made. The uniformity of flux at the light pipe exit was within 10 percent of the average, which was considered acceptable. The water cooling system worked satisfactorily at the low power input levels available at the ACTF. It was concluded that the CNRS test program in August 1979 should be carried out.

Table 2. Flux measurements at ACTF

Measurement plane	Average flux (W/cm ²)	Transmission factor (percent)
Diverter inlet	54.1	100
Diverter outlet	42.2	78
Sample chamber outlet	13.5	25

Data are normalized to a direct insolation of 875 W/m².

TEST PROGRAM AT THE CNRS SOLAR FURNACE, AUGUST 1979

The light pipe assembly was tested at the CNRS 1000 kW Solar Furnace during the period August 20-24, 1979. Photographs of the solar furnace and the light pipe assembly installed in the focal room of the facility are shown in Figures 3 through 5. The diverter inlet was positioned at the nominal focus of the solar furnace and the sample chamber was oriented vertically with provisions for installation of a soil pan at the bottom of the sample chamber.

The objectives of this test program were:

- (1) To perform an overall checkout of the light pipe cooling system, verify the durability of the reflecting surfaces under exposure to the full solar flux available at the facility, and identify design deficiencies.
- (2) To measure the flux throughput at the diverter exit, the sample chamber exit, and at several intermediate positions within the sample chamber.

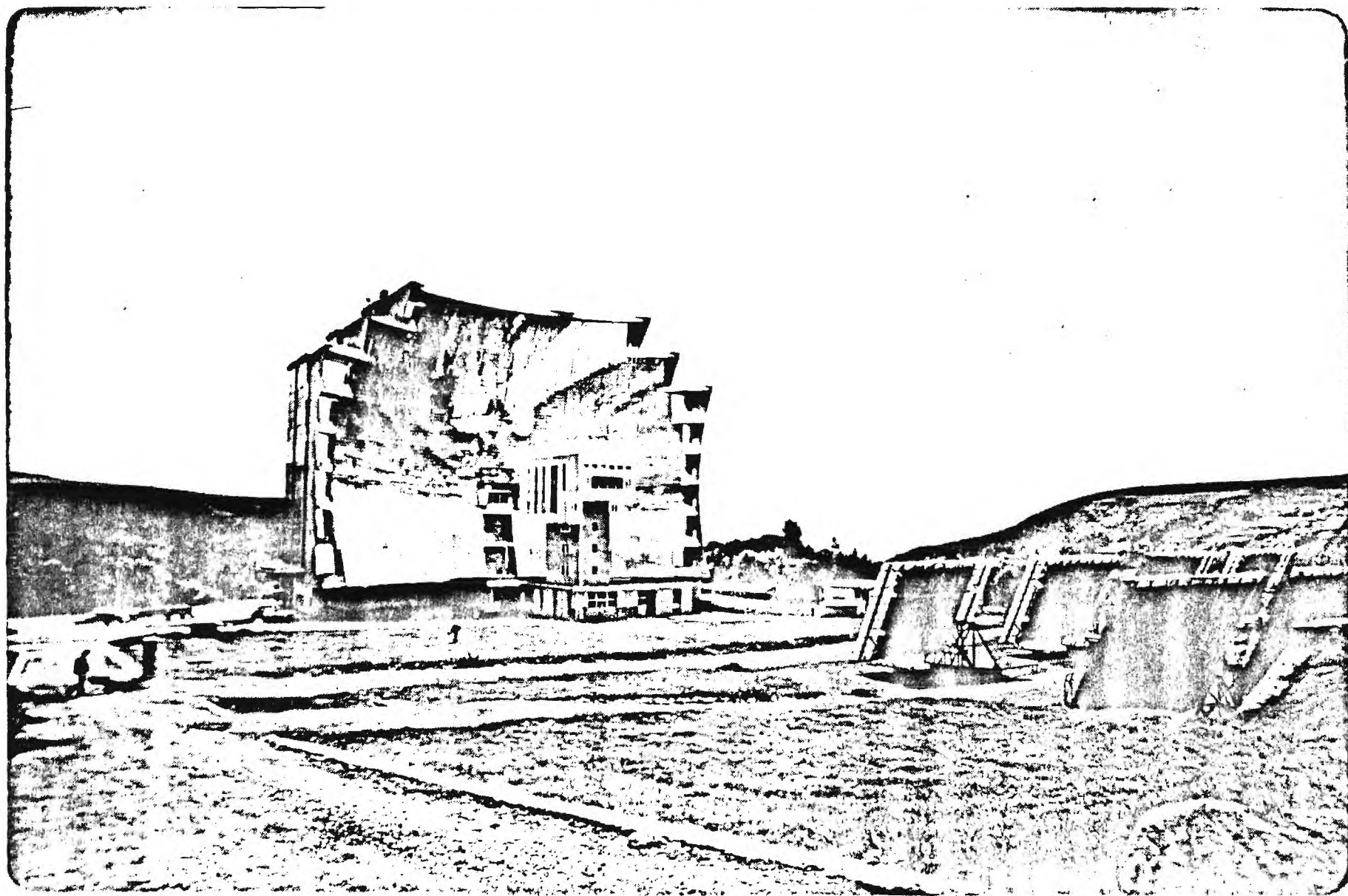
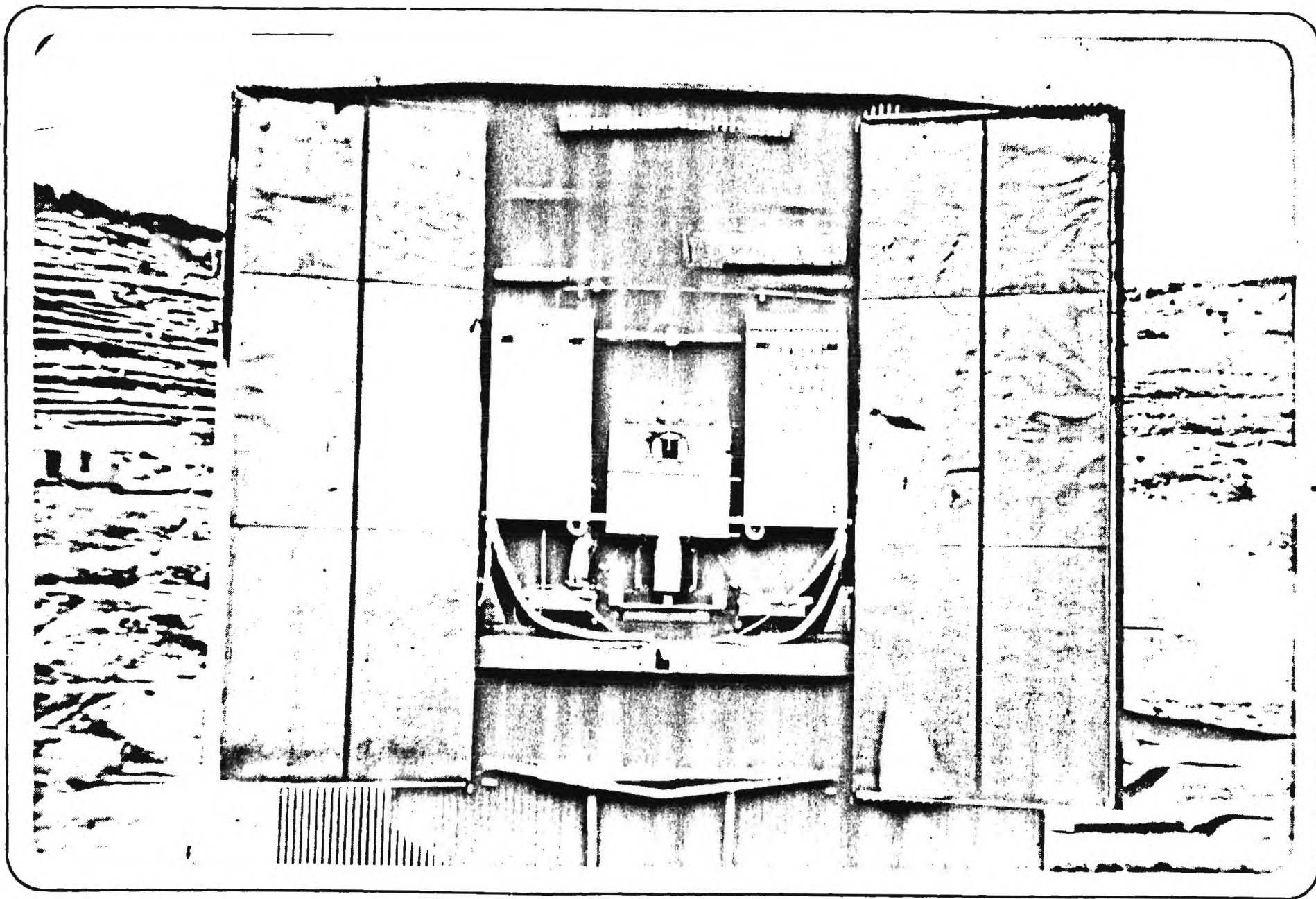


Figure 3. General view of CNRS 1000 kW Solar Furnace.

Figure 4. SAI light pipe assembly in focal room of CNRS 1000 kW Solar Furnace.



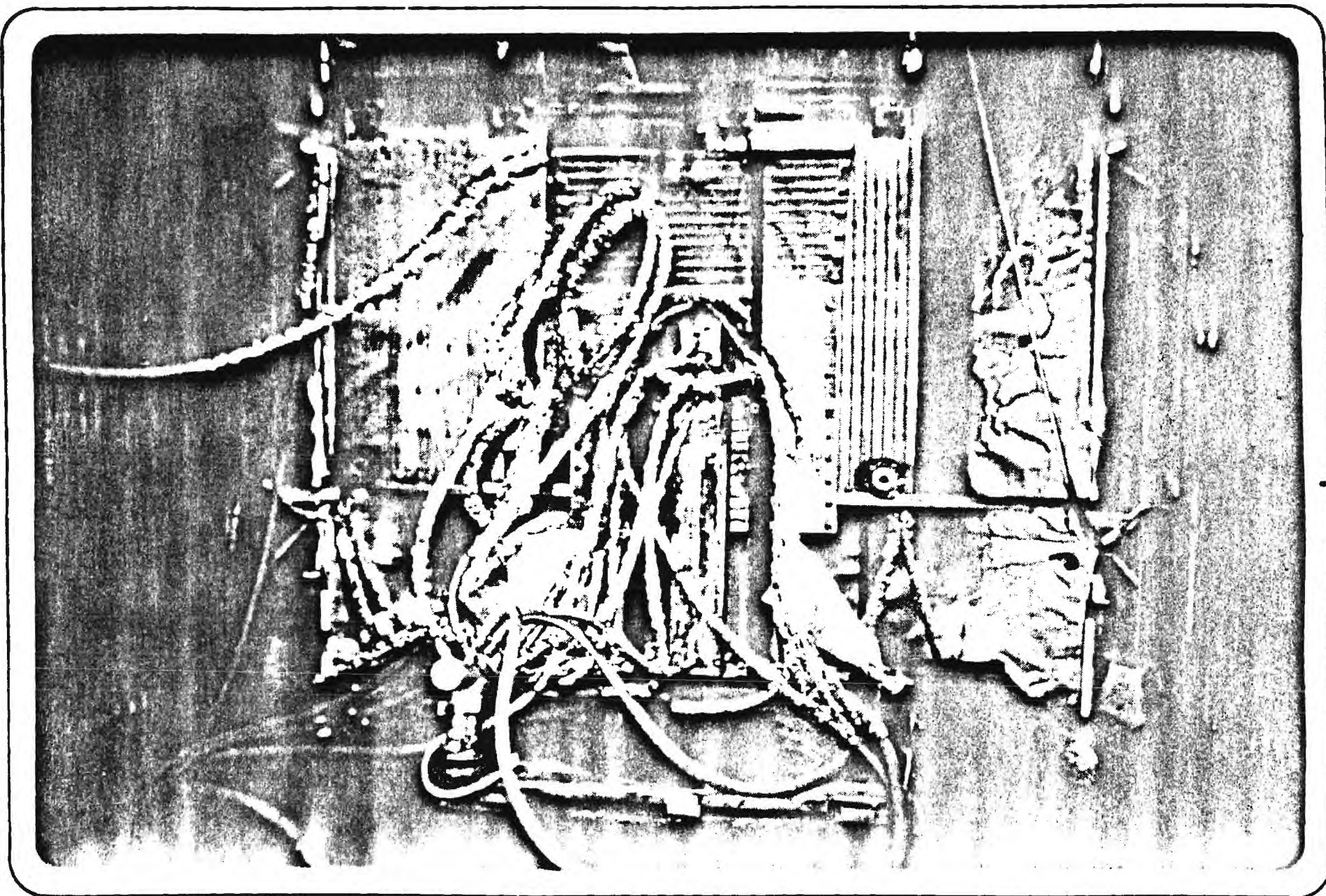


Figure 5. Interior of focal room of CNRS 1000 kW Solar Furnace during August 1979 test program.

- (3) To check the survivability of thin shutter materials which were to be used without cooling for pulse-shaping shutters.
- (4) To run several soil samples for qualitative inspection of their responses to high-intensity radiant energy, their tendency to deposit dust on the chamber walls, and any unexpected behavior.
- (5) To make trial exposures of movie films.

Approximately 70 runs were made during this test period, about 42 for calorimetry at various locations, 11 for evaluating shutter materials, five for soil tests, and 12 by CNRS for calorimetry.

The calorimetry measurements were in rather good agreement with similar measurements made at the ACTF, considering the difference in characteristics of the two facilities; flux throughput was found to be about 33 percent (versus 25 at the ACTF) and flux uniformity was found to be within about 10 percent of the average (the same value measured at the ACTF).

The cooling system worked satisfactorily except for failure of a water cooled shield which matched the square inlet aperture of the diverter to a circular aperture in the CNRS shields. Boiling was heard in some areas of the equipment, but this was controlled by increasing cooling water flow rates and rearranging hose connections to minimize the formation of air pockets.

Of the shutter materials, specular silver plating on copper and brass substrates and polished silver alone withstood five to ten seconds of exposure at the diverter outlet plane. Aluminum, nickel, diffuse silver plated on brass, stainless steel, and combinations of silver and nickel platings failed in two to six seconds. The shutter material tests indicated that none of the thin, uncooled materials could be expected to withstand the flux at the diverter exit for more than about ten seconds; synchronizing of the water-cooled shutters and the pulse-shaping shutters would thus be a critical requirement.

The five soil tests were made on separate samples obtained from the lawn near the CNRS focal building. Fusing of particles, darkening, and ejection of material was observed on vegetation-free soils. The vegetation on one soil burned immediately upon exposure and filled the sample chamber with smoke, thereby protecting the soil surface from fusing and charring. Color movies were made on four of the soils; the first run was used for exposure measurement. There was a pronounced tendency for dirt particles to collect on the sample chamber walls during the soil runs, necessitating cleaning after each run to prevent deterioration of the flux level at the soil plane.

The following system modifications were identified for future tests:

- (1) Larger window areas were required in the sample chamber to allow most of the soil surface to be observed by cameras; this was a high-priority item because of the importance of the movie data.
- (2) A hinged panel was needed on the sample chamber to permit cleaning of the walls after each run.
- (3) A system for heating the circulating water was needed to prevent condensation of atmospheric moisture on the sample chamber walls and the cooling system piping should be arranged to avoid air pockets.

- (4) Several movie cameras were needed to obtain adequate documentation from different perspectives.
- (5) A stiffer frame was needed to support the apparatus rigidly.

TEST PROGRAM AT THE CNRS SOLAR FURNACE, FEBRUARY 1980

The first test program whose objective was to acquire soil response data in a systematic manner was conducted at the CNRS 1000 kW Solar Furnace during the period February 18 through March 7, 1980. This program included the acquisition of extensive photographic data, the use of a large number of diagnostic techniques by SAI, and a light transmission experiment conducted by the University of Denver Research Institute (DRI).

It was determined at a meeting of DNA and its contractors in January 1980 that the primary documentary movies should be made on Eastman Kodak Linagraph Shellburst 2476 film at 200 frames per second. This is a black and white film with very wide exposure latitude, developed for photographing events which have wide variations in brightness. It was planned that densitometry scales would be spliced onto each roll prior to processing, so that quantitative measurements of brightness could be made. It was also decided that a red filter would be used in order to minimize the recording of scattered light. DRI was in possession of suitable movie cameras owned by DNA, and furnished four D. B. Milliken 4CD cameras for the test program. These are electrically-driven, pin-registered, 16 mm cameras, capable of framing rates up to 500 images per second.

Tests of the camera, film, filter and processing combinations began at GIT on February 1, 1980. Three Kodak Wratten filters were tested, #25 with a short wavelength cutoff at 5900 Angstroms, #70 with a short wavelength cutoff at 6500 Angstroms, and #92 with a short wavelength cutoff at 6200 Angstroms. Using a Kodak Versamat film processor, speeds of 2, 3, 4, and 6 feet per minute were used to process the film. Light meter readings were taken on a Kodak 18 percent neutral gray test card prior to exposing each test film using an assumed ASA setting of 250, and two different graded gray scales and a color control card were photographed. The resulting test negatives were used to evaluate the processing, determine if an equivalent ASA speed of 250 was appropriate, and select an exposure factor to compensate for the red filter. At a processing speed of 4 feet per minute, satisfactory agreement between the light meter readings at ASA 250 and the negative densities was found. It was then determined that a filter correction of four stops was needed for the #70 Wratten filter.

Two GIT engineers arrived at the CNRS Solar Furnace on February and participated with SAI personnel in setting up apparatus in the focal room, including equipment assembly, documentation of equipment positions (for future geometric analyses), and hookup to the 60-Hertz power system provided by GIT. A description of the movie camera arrangement is shown in Table 3 and a photograph of the interior of the focal room is shown in Figure 6.

Testing began on February 18 with characterization of the light pipe, radiation flux calibrations, and trial light meter readings on samples of sand. There followed seven days without sun, during which camera exposure discrepancies were recognized and plans made for resolution. When testing resumed on February 26, trial exposures were made using a fourth DBM camera and the films were processed on-site. Beginning with Test No. 35 on February 27, the camera settings shown in Table 3 were adopted.

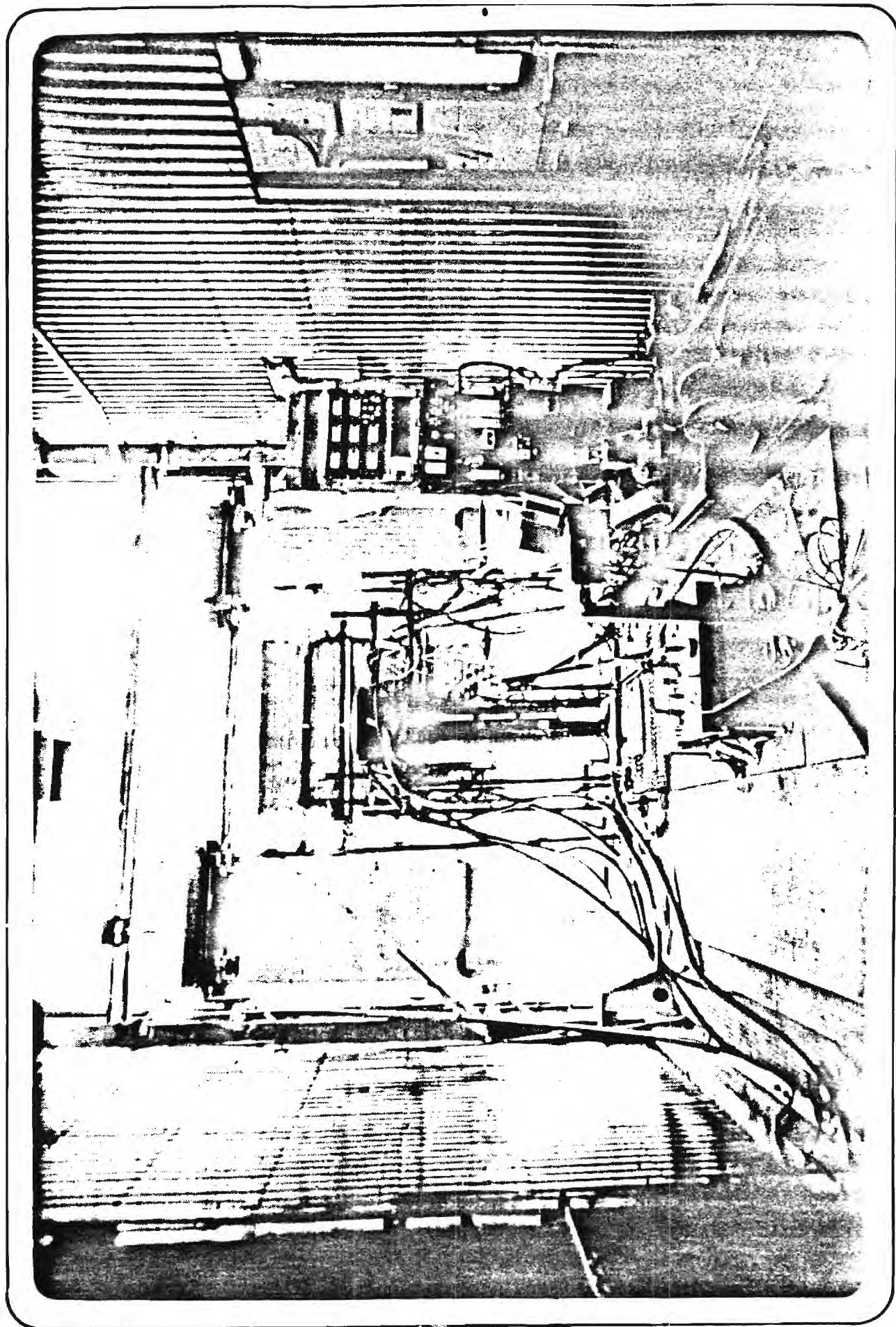


Figure 6. Interior of focal room of CNRS 1000 kW Solar Furnace during February-March 1980 test program.

Table 3. Movie camera arrangement, February-March 1980

Camera	Settings	View and rationale
DBM No. 1	f:22 1/3000 s #70	Downward view of sample surface, because cameras pointed horizontally could not see soil surface
DBM No. 2	f:16 1/3000 s #70	Horizontal view of bottom window in sample chamber, to permit particle velocity measurements immediately above sample surface
DBM No. 3	f:16 1/3000 s #70	Horizontal view of all four windows in sample chamber, to permit particle velocity measurements along entire chamber length
Bolex H16	f:5.6 1/125 s 3.00 ND	Kodachrome 25 film, 24 frames per second, held on tripod with view similar to DBM No. 1 to document appearance of sample in color

During this test program a total of 152 runs were performed. Sixty runs were made on "parametrically chosen" soils, 56 runs were made on natural (undisturbed) soils, and five runs were made on man-made surfaces such as concrete and floor tiles; the remaining runs were for apparatus checkout and calibrations. The DBM movie cameras using Linagraph Shellburst film were operated by GIT for every test and the Bolex camera using Kodachrome 25 film was operated on most tests. Before- and after-test photographs of each test specimen were made on 35 mm color slides with a reference color chart in the picture. Brightness measurements using a Minolta 1-degree spot meter were recorded before and after exposure of each specimen.

A minimum-run contingency test plan was developed in association with SAI early in the test program. This was necessary in case the number of good test days was not sufficient to allow all samples to be tested. The weekend preceding the last week of testing was devoted to adapting the light pipes and experimental set-up to accommodate the DRI transmission experiment. This required modification of the light pipe. By this time all of the undisturbed soils had been tested. Approximately 80 sample exposures had been made.

All Milliken cameras and the Bolex camera were able to continue to record the remaining 42 tests conducted during the third week. The test series consisting of the exposure of approximately 112 different soil samples was completed on Friday, March 7, 1980 at 3:11 p.m. when solar insolation decreased due to cloudy conditions.

A total of 99 rolls of Kodak Linagraph Shellburst film 2476 were hand carried back to the United States and subsequently returned to LASL for processing. This lot included 79 rolls of film from cameras 1, 2 and 3, two control rolls and 18

rolls of film exposed by DRI. Six rolls of Kodachrome movie film from the Bolex camera were also returned for processing along with 21 rolls of 35 mm film. Copies of these slides and color movie films were supplied to SAI along with a titled set of all runs including before and after slides and the movies of the tests. This color test movie is approximately 1200 feet in length. A film log indicating the approximate content of each roll of linagraph film was also generated. This was to facilitate processing by LASL and allow the results to be cataloged.

At a program review meeting in May 1980, personnel from LASL expressed the judgment that all films from DBM Camera No. 1 were overexposed except at the initial opening of the shutters. This film was exposed with a #70 Wratten filter in the optical path, which transmits less than 0.1 percent of radiation of a wavelength less than 6415 Angstroms. The high-density image recorded by DBM Camera No. 1 may be due to black body radiation emitted by the soil as its temperature increases. This radiation is above the lower wavelength limit of the filter and below the upper wavelength sensitivity of the film (7000 Angstroms). As the soil sample heats up, the amount of black body radiation between 6415 and 7000 Angstroms will increase in proportion to the fourth power of the absolute temperature. Although the Linagraph Shellburst films were judged to be overexposed, this was preferable to underexposure because all data can be retrieved due to the four decade dynamic range of the film.

TEST PROGRAM AT THE CNRS SOLAR FURNACE, SEPTEMBER 1980

The second test program whose objective was to acquire soil response data in a systematic manner was conducted at the CNRS 1000 kW Solar Furnace during the period September 8 through 26, 1980. At a meeting of the several DNA contractors participating in this program on May 29, 1980, the following modifications of procedures used in the February-March program were defined:

- (1) The film used in the No. 1 movie camera should be changed from Linagraph Shellburst to Kodachrome 25 in order to acquire color information on all runs; the value of black and white densitometry measurements on films viewing the soils at oblique angles was deemed marginal.
- (2) The No. 2 and 3 movie cameras should be changed from 16 mm to 35 mm and the positioning of these cameras should be rearranged in order to increase the image sizes used for densitometry traces.
- (3) Other changes, within SAI's sphere of responsibility, should be made in order to insure that data collected in the field were compatible with program needs; specifically, direct measurement of dust and air temperature, collection of dust particles, pulse shaping, and the use of a Knollenburg probe to sample dust particle sizes were identified as being important.

LASL was able to supply three 35 mm Mitchell movie cameras with film magazines, motor drives, and suitable lenses and DRI supplied one 16 mm DBM camera which had been used in the February-March test program. The required mounting apparatus was assembled at Georgia Tech and trial films were exposed and processed. GIT purchased the necessary film supply, based on the filming time experienced in the February-March test program, and shipped the equipment and film to the CNRS facility.

GIT personnel arrived at the CNRS Solar Furnace on September 5 and participated with SAI personnel in setting up the experiment. The arrangement of the cameras is described in Table 4 and a photograph of the interior of the focal room is shown in Figure 7.

Table 4. Movie camera arrangement, September 1980

Camera	Settings	View
DBM No. 1	fill 1/2880 s 1.00 ND	Downward view of sample surface through lowest window, Kodachrome 25 film, 100 frames/s
Mitchell No. 2	f:16 1/2400 s #70	Horizontal view of two lower sample chamber windows, Linagraph Shellburst film, 100 frames/s
Mitchell No. 3	f:16 1/2400 s #70	Horizontal view of two upper sample chamber windows, Linagraph Shellburst film, 100 frames/s

During this test period a total of 276 runs were performed, of which 238 were with soil or other test surfaces and 38 were for equipment checks or calibration. Because the test runs were being made more rapidly than expected, one of the Mitchell movie cameras was abandoned about September 18 to conserve film. The supply of Linagraph Shellburst film was finally exhausted on September 24, although runs were continued until midafternoon on September 25. All runs were photographed using the DBM movie camera with Kodachrome 25 film and before- and after-test slides were made on each specimen as had been done in February-March. Brightness measurements were recorded before and after exposure of each specimen.

The following collection of photographic film was returned to the U. S. for processing and analysis:

- 53 rolls, Kodachrome 25, 35 mm, 36 exposures
- 2 rolls, Ektachrome 160, 35 mm, 36 exposures
- 5 rolls, Ektachrome 400, 35 mm, 36 exposures
- 25 rolls, Kodachrome 25, 16 mm movie, 100 feet
- 2 rolls, Ektachrome 160, 16 mm movie, 100 feet
- 16 rolls, Linagraph Shellburst, 35 mm movie, 500 feet

GIT had all color film processed, the color movies copied, and distributed appropriate films to SAI and DNA. The exposed black and white movie films were turned over to a DNA office in Albuquerque, New Mexico for handling. The DBM movie camera was returned to DRI and the Mitchell cameras were held at GIT pending instructions for disposition.

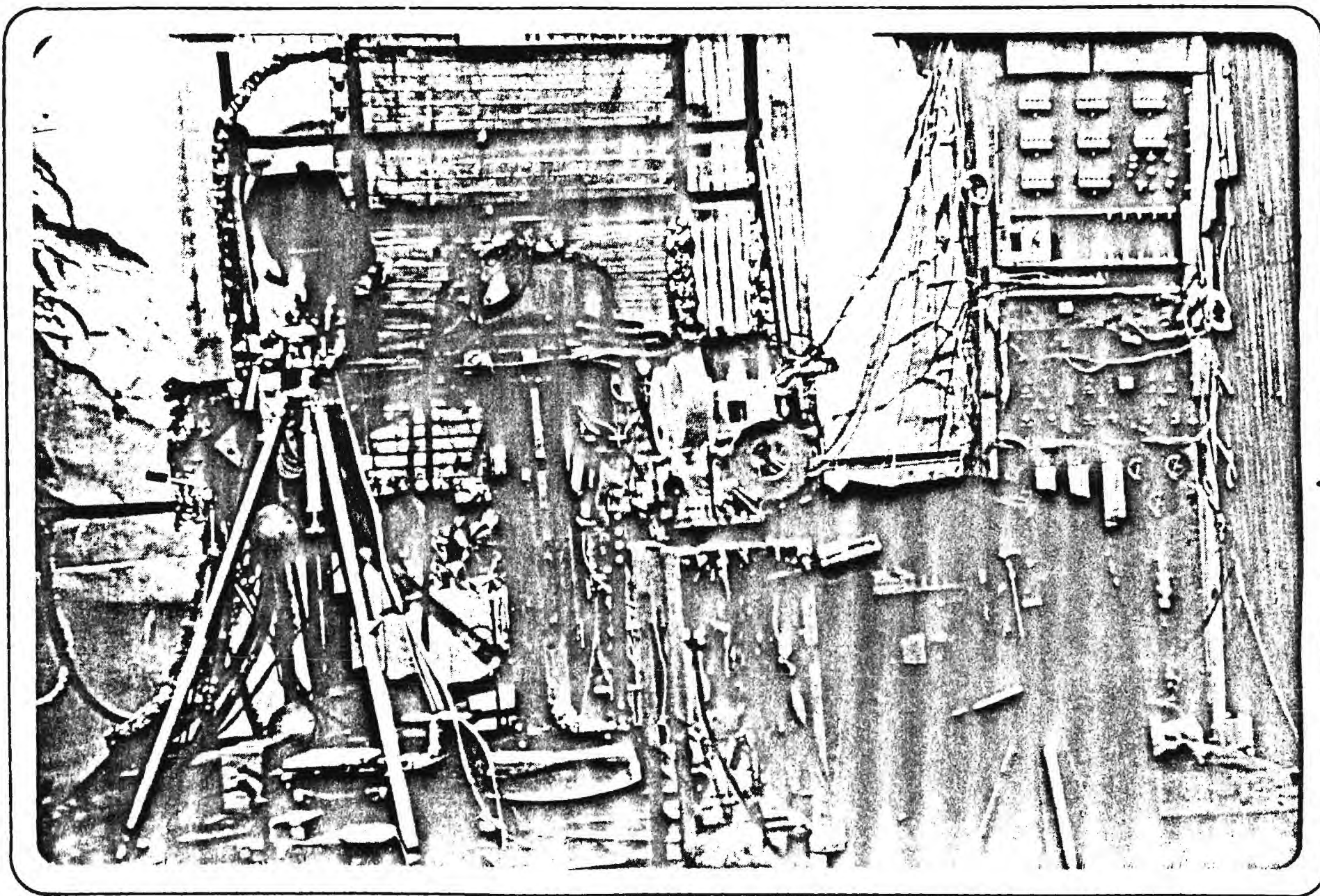


Figure 7. Interior of focal room of CNRS 1000 kW Solar Furnace during September 1980 test program.

A program review meeting was conducted on October 24 to critique the test program. At this time, there appeared to be a consensus among DNA's program contractors that data reduction should be carried out on at least one soil before additional test programs are attempted at the CNRS Solar Furnace.

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been reached on this research program:

- (1) The basic concept of the SAI designed and constructed light pipe was adequate to permit tests of soils exposed to simulated thermal pulses from nuclear weapons. The construction and the diagnostic instrumentation were not well executed, however, and serious equipment failures were experienced on each test program. For example, no soil tests with shaped pulses were ever completed during a total of 498 runs conducted at the CNRS 1000 kW Solar Furnace.
- (2) Photographic techniques appear to have been refined to the stage that adequate documentary movies can be made. Color movies are correctly exposed but further adjustment of exposure on black and white films may be required to facilitate processing by scanning densitometers. Compromises with respect to filtering may be required to overcome the tendency of emitted radiation to increase film exposure levels.
- (3) A large body of experimental data on many soils and other surfaces has been acquired. Most of this information has not yet received adequate analysis. The analysis appears to be a very formidable task, but should be completed for at least a few soils before further measurement programs are undertaken.

The following recommendations with respect to future work are offered:

- (1) Since analysis of the experimental data has not been completed, it is not yet clear whether the soil measurements are suitable to meet DNA's program needs. It is recommended that the entire matrix of experimental data for one soil be assembled and inspected for usefulness. The data considered should include movies, information of temperatures, particulate material collected, weight losses, soil composition, changes in brightness and visual appearance, and anything else available. The collection should then be reviewed by manual techniques to identify those conclusions which might be obtained, such as temperatures and dust loadings as functions of time, particle velocities, redundant determinations from separate runs, etc. If it appears that detailed analysis is warranted, the collection should be processed to extract correlations meeting the DNA's needs, for the single soil selected. The feasibility of processing data from other soils can then be established from the patterns identified under this limited study.
- (2) If additional soil measurement programs are undertaken in the future, these should emphasize the acquisition of high quality physical data rather than the survey of large numbers of soils. The rule should be that all diagnostic instrumentation and measurement apparatus will be functioning correctly and calibrated before a run is made. If a piece of diagnostic data, such as a thermocouple output, has so little value that calibration is not worthwhile, then the instrument should be removed in order to simplify the experiment; conversely, if data are worth

measuring, they are worth measuring correctly. The practice of abandoning instruments when they fail, but continuing to expend solar furnace time and personnel effort to run more specimens, can no longer be justified with the contention that many soils need to be surveyed.

FINAL REPORT

DNA _____

TECHNIQUES FOR INVESTIGATING MATERIALS IN A RADIANT HEAT ENVIRONMENT

31 August 1981

**Prepared for
DEFENSE NUCLEAR AGENCY
Washington, D. C. 20305**

**Under
Contract No. DNA 001-78-C-0261**

**THIS WORK SPONSORED BY THE DEFENSE NUCLEAR AGENCY
UNDER RDT&E RMSS CODE B3440 81466Y99QAXSG00009**

GEORGIA INSTITUTE OF TECHNOLOGY

**A Unit of the University System of Georgia
Engineering Experiment Station
Atlanta, Georgia 30332**



DNA _____

TECHNIQUES FOR INVESTIGATING MATERIALS
IN A RADIANT HEAT ENVIRONMENT

Georgia Institute of Technology
Engineering Experiment Station
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SUMMARY

The long range objective of this program is to measure quantitatively the behavior of soil specimens while they are subjected to simulated thermal pulses from nuclear weapons. This report describes participation by the Georgia Institute of Technology in a series of test programs for the Defense Nuclear Agency to meet the above objective. Georgia Tech, Science Applications, Incorporated, and the University of Denver Research Institute conducted measurement programs during 1979 and 1980 at the CNRS 1000 kW Solar Furnace in France to acquire data on the behavior of soils under simulated thermal pulses.

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SECTION I

INTRODUCTION

Prediction of the effects of nuclear weapons is of interest to the Defense Nuclear Agency (DNA) for assessment of the probable damage to targets under various military scenarios. In order to preform these predictions by analytical methods, it is necessary that certain transport properties of the media surrounding the point of detonation be known. In this investigation, the transport properties of the atmosphere near the surface of the ground were of interest.

Under certain combinations of soil type and radiant thermal fluxes from the fireball, it is possible for soil materials, such as particles, water vapor, and smoke from burning vegetation, to be ejected into the atmosphere above the soil surface. If this occurs, the transport properties of the atmosphere are altered and the shock wave, arriving a few seconds after the thermal pulse, behaves differently than if it were traveling through undisturbed air. In order to perform analytical modeling of the shock wave propagation, the transport properties of the atmosphere must be known or estimated. The purpose of this program was to acquire such information by an experimental method.

Solar furnaces provide high radiant heat fluxes with spectral distributions reasonably approximating those emitted by nuclear weapon fireballs. The Centre National de la Recherche Scientifique (CNRS) 1000 kW Solar Furnace at Odeillo, France has the most suitable characteristics of any such facility in the world for simulating the effects of nuclear weapon fireballs on soils: a very high incident flux at the focus (about 1,200 W/cm²) and a high enough power level to illuminate relatively large specimens (about 1 MW of thermal power).

Science Applications, Incorporated (SAI) and the Georgia Institute of Technology (GIT) have worked cooperatively under separate contracts from DNA to carry out a research program for evaluation of soil specimens exposed to simulated nuclear weapon thermal pulses. This report describes work performed by GIT during the period March 1979 through December 1980 under contract DNA001-78-C-0261.

RESPONSIBILITIES OF THE GEORGIA INSTITUTE OF TECHNOLOGY

GIT was responsible for certain clearly defined activities under this cooperative research program for DNA:

- (1) To serve as DNA's liaison with CNRS, including coordination with CNRS personnel on test schedules, test plans, and related matters.
- (2) To perform coordination between CNRS and the numerous DNA contractors who were active on the program at various times, including SAI, the University of Denver Research Institute (DRI), and others.
- (3) To make payments to CNRS, through GIT's Research Services Agreement with CNRS, for solar furnace charges, professional services of CNRS personnel, and reimbursement of freight expenses.
- (4) To attend program meetings and participate in the planning of test programs and the review of test results.

- (5) To conduct proof testing of the SAI diverter and light pipe assembly during July 1979, prior to the first test program at the CNRS Solar Furnace.
- (6) To procure and transport assigned equipment and supplies for test programs at the CNRS Solar Furnace in August 1979, February-March 1980, and September 1980.
- (7) To furnish two engineers at the CNRS Solar Furnace during the three test programs, for operation of photographic equipment, work coordination, and assisting in the setup and operation of test equipment.
- (8) To make all photographic records of the tests (excluding the light transmission experiment conducted by DRI in March 1980), handle processing of all color films, distribute photographic records to the team members, and forward black and white films to a DNA office in Albuquerque, New Mexico for processing.
- (9) To prepare and distribute written inputs for test program reports, including descriptive materials and logs of the photographic films.

TEST REQUIREMENTS

The incident beam at the CNRS 1000 kW Solar Furnace arrives at the focus from an approximately horizontal direction. DNA and its contractors defined the following test requirements for the soil evaluation tests at that facility:

- (1) The soil sample should lie in a horizontal plane with the incident radiation arriving downward from a direction approximately normal to the sample plane.
- (2) The atmosphere above the soil should be surrounded by a column with reflecting walls so that the atmosphere appears to be an infinite medium; the height of the column should be two to four meters.
- (3) The linear dimension(s) of the sample should be 15 to 30 cm (6 to 12 inches); a round or square sample configuration is preferred.
- (4) The transport properties of the atmosphere must be determined as functions of time and height above the sample plane, beginning at the time of initiation of the thermal pulse and ending at the time of shock wave arrival for the weapon parameters under consideration.
- (5) The soil behavior must be documented photographically and particle samples should be collected at various heights above the specimen plane.
- (6) The optical system used to turn or otherwise process the beam of concentrated solar radiation arriving at the focal zone of the solar furnace must cause a minimum attenuation of the incident flux.

In order to conform to the test requirements, SAI designed and constructed a water-cooled light pipe with a curved section at the top to turn the incident focused solar radiation along the axis of the pipe. The light pipe was mounted

vertically, with the inlet aperture of the curved section (the "diverter") positioned at the focus of the solar furnace. The soil specimen was usually placed in a pan at the bottom of the pipe, lying in a horizontal plane (some runs were conducted with the sample pan supported inside the light pipe rather than at the bottom). Various sampling ports and transparent windows were placed along the length of the light pipe (the "sample chamber") in order to permit samples of the atmosphere to be withdrawn, temperature probes to be inserted, and photographs to be made during the runs.

A preliminary evaluation of candidate materials for the light pipe wall was conducted by GIT at the CNRS Solar Furnace in April 1979, during a test program for another sponsor; these tests provided a basis upon which SAI could select wall materials and reflective coatings. A light pipe assembly was proof tested at the Advanced Components Test Facility (a solar thermal test facility operated by GIT for the Department of Energy and located on the GIT campus) in July 1979; this test gave some assurance that the light pipe would survive exposures in a solar furnace before resources were committed for a trip to France. Three test programs were conducted at the CNRS 1000 kW Solar Furnace in August 1979, February-March 1980, and September 1980; these programs conducted soil exposure experiments and collected data for subsequent analysis. SAI was responsible for the light pipe and experiment design, with input from other members of DNA's project team; GIT's responsibilities have been listed earlier.

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SECTION II

EXPERIMENTAL WORK

TESTS OF CANDIDATE WALL MATERIALS

GIT conducted tests of candidate light pipe wall materials at the CNRS 1000 kW Solar Furnace during the period April 18 through May 2, 1979. At that time, a test program was underway on another research contract and the addition of a small number of samples for this DNA program could be accomplished without significant costs, except the costs of the specimen materials. SAI furnished approximately 30 specimens and Georgia Tech furnished 12 specimens. These tests provided a basis for selecting light pipe construction materials.

Weather conditions at the solar furnace during the test period were very poor and only nine specimens were run. The specimens were exposed to the full flux available at the focal point of the facility at the time the tests were conducted. Front surface temperatures were measured by an infrared optical pyrometer, back surface temperatures were measured on some samples by thermocouples, and 16 mm color movies were made on all samples. Essential data, as determined from the movie records, are shown in Table 1. The aluminum reflecting films on three substrates were applied by vacuum evaporation. The silver films on the remaining substrates were electroplated and polished to give the best smoothness and specular reflectance possible; the steel substrates retained some evidence of tool marks.

The movies and the data shown in Table 1 show that silver is superior to aluminum as a reflective material for the light pipe walls. Copper seems to be the preferred substrate because its high thermal conductivity causes heat to move away from the surface rapidly; it and brass can also be polished more easily than steel. These tests, on uncooled samples, indicated that the light pipe should be expected to survive irradiation near the focus of the solar furnace.

PROOF TESTING OF THE LIGHT PIPE ASSEMBLY

SAI constructed its proposed light pipe assembly, consisting of a curved, beam-turning section (the diverter) and a four-foot long straight section (the sample chamber) in early 1979. The diverter was built from brass with all surfaces exposed to the solar flux being silver plated and the sample chamber was made from steel with exposed surfaces silver plated. It was generally agreed that a proof test at a solar facility in the U. S. was needed before time and resources were expended to conduct testing at the CNRS Solar Furnace in France. SAI proposed to conduct proof testing at the Central Receiver Test Facility (CRTF), a solar thermal test facility operated by Sandia Laboratories for the Department of Energy in Albuquerque, New Mexico. The CRTF's schedule could not accommodate a test of the SAI device before a test program scheduled at CNRS in August 1979.

It was determined that the proof testing should be conducted at the Advanced Components Test Facility (ACTF), a solar thermal test facility operated by GIT for the Department of Energy. These tests were conducted during the period July 23-28, 1979. Photographs of the ACTF and the light-pipe assembly are shown in Figures 1 and 2.

The objectives of the proof testing were:

Table 1. Solar Furnace measurements of wall materials

Material	Incident flux (cal/cm ² -s)	Maximum fluence (cal/cm ²)	Remarks
Aluminum plated on brass	273	2785	Melting began at 2129 cal/cm ² ; pouring began at 2348 cal/cm ² ; Run II/35
Aluminum plated on copper	173	2543	No damage at end of test; 2 in. diameter by 1/4 in. thick; Run I/12
Aluminum plated on steel	274	2795	Melting began at 1644 cal/cm ² ; Run II/37
Silver plated on brass	186	2734	No damage at end of test; 2 in. diameter by 1/4 in. thick; Run I/11
Silver plated on copper	192	2803	No damage at end of test; 2 in. diameter by 1/4 in. thick; Run I/10
Silver plated on copper	229	4946	Slight decrease in reflectance after test; 2 in. diameter by 1/4 in. thick; Run I/16
Silver plated on copper	273	4778	Sample melted at end of test; Run II/33
Silver plated on steel	274	4740	Particles ejected at 4274 cal/cm ² ; melting began at 4357 cal/cm ² ; Run II/34
Silver plated on steel	273	5324	Particles ejected at 4750 cal/cm ² ; Melting began at 4859 cal/cm ² ; Run II/36

- (1) To determine whether the cooling water system was adequate to protect the assembly from damage during run times of to ten seconds.
- (2) To measure the flux at the diverter exit and at the sample chamber exit, so that the flux at these planes during tests at the CNRS Solar Furnace could be estimated.

Although the characteristics of the ACTF and the CNRS Solar Furnace do not match very well (the rim angle is 45 degrees at the ACTF versus 74 degrees at CNRS and the power level into a six-inch aperture is about 25 kW at the ACTF versus about

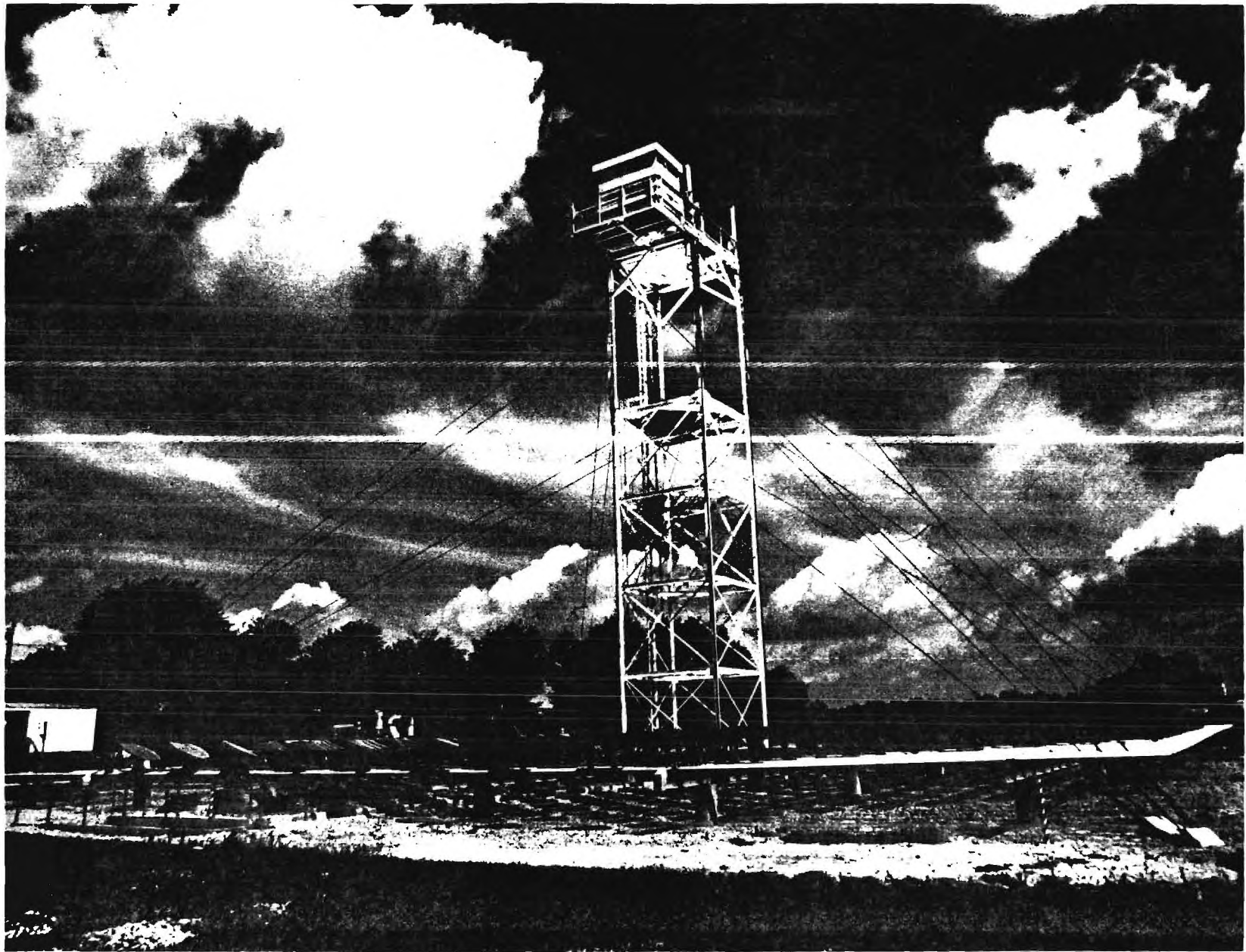


Figure 1. General view of the Advanced Components Test Facility.

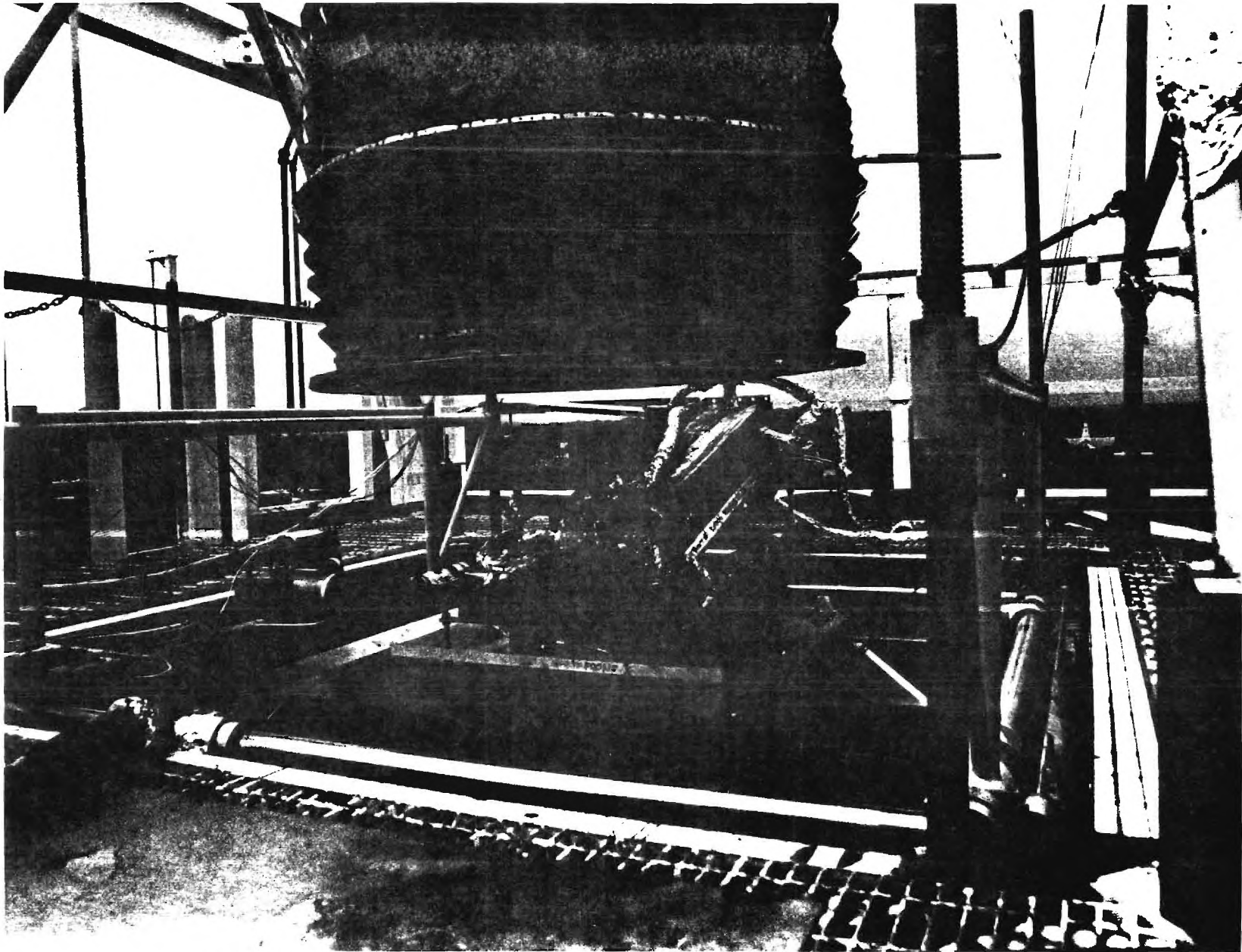


Figure 2. SAI light pipe assembly installed at ACTF for proof testing.

250 kW at CNRS) the high cost of an unproductive trip to France seemed to warrant testing under the conditions available at the ACTF.

A total of 19 runs were made, 24 with the diverter and sample chamber and six with the diverter only. Fluxes at the three measurement planes were measured using eight Hycal calorimeters mounted on an aluminum heat sink plate. Throughput fluxes for a typical run are shown in Table 2; the overall flux throughput of 25 percent was about half the expected value, but if that fraction of the inlet flux were obtained at CNRS, useful measurements could be made. The uniformity of flux at the light pipe exit was within 10 percent of the average, which was considered acceptable. The water cooling system worked satisfactorily at the low power input levels available at the ACTF. It was concluded that the CNRS test program in August 1979 should be carried out.

Table 2. Flux measurements at ACTF

Measurement plane	Average flux (W/cm ²)	Transmission factor (percent)
Diverter inlet	54.1	100
Diverter outlet	42.2	78
Sample chamber outlet	13.5	25

Data are normalized to a direct insolation of 875 W/m².

TEST PROGRAM AT THE CNRS SOLAR FURNACE, AUGUST 1979

The light pipe assembly was tested at the CNRS 1000 kW Solar Furnace during the period August 20-24, 1979. Photographs of the solar furnace and the light pipe assembly installed in the focal room of the facility are shown in Figures 3 through 5. The diverter inlet was positioned at the nominal focus of the solar furnace and the sample chamber was oriented vertically with provisions for installation of a soil pan at the bottom of the sample chamber.

The objectives of this test program were:

- (1) To perform an overall checkout of the light pipe cooling system, verify the durability of the reflecting surfaces under exposure to the full solar flux available at the facility, and identify design deficiencies.
- (2) To measure the flux throughput at the diverter exit, the sample chamber exit, and at several intermediate positions within the sample chamber.

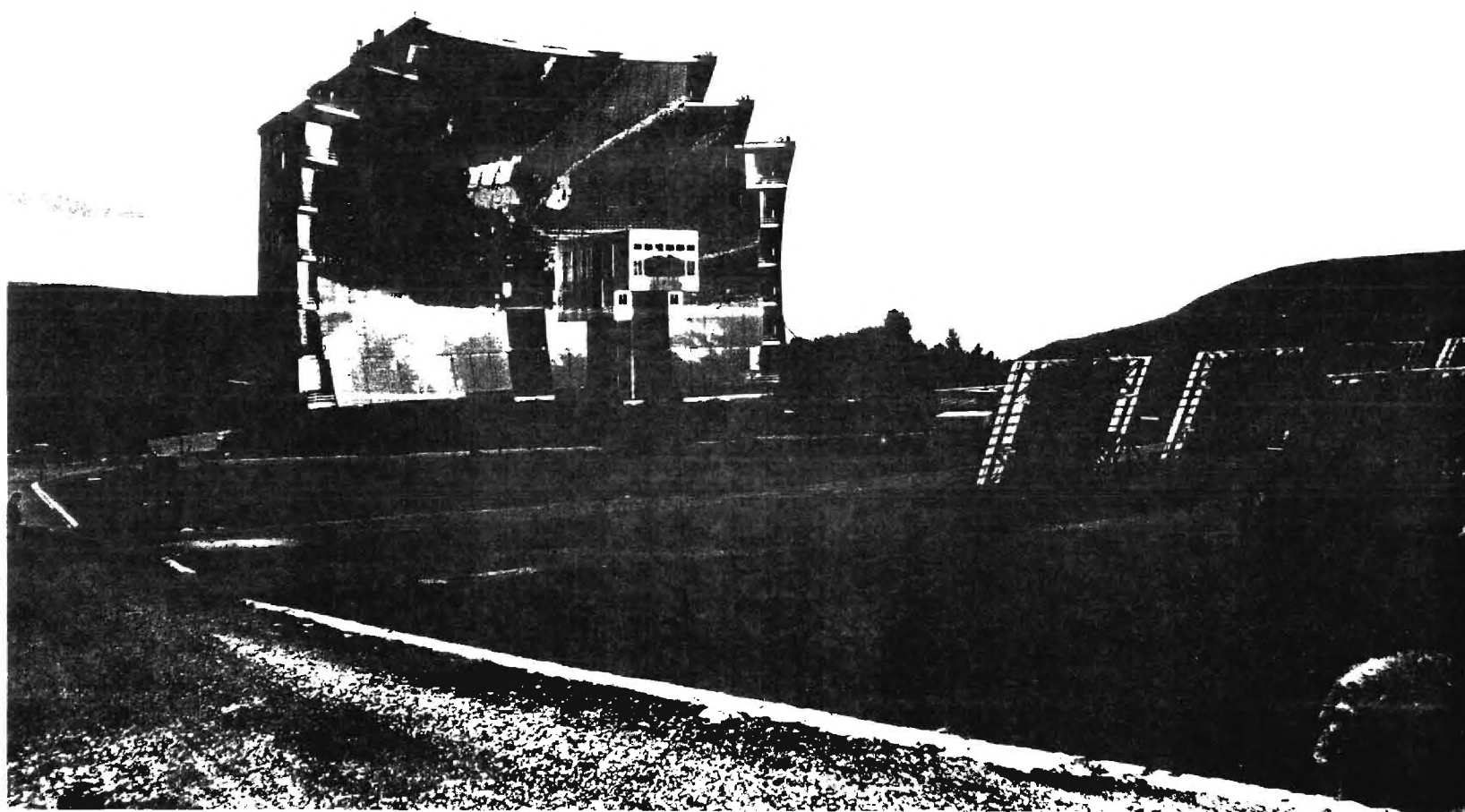


Figure 3. General view of CNRS 1000 kW Solar Furnace.

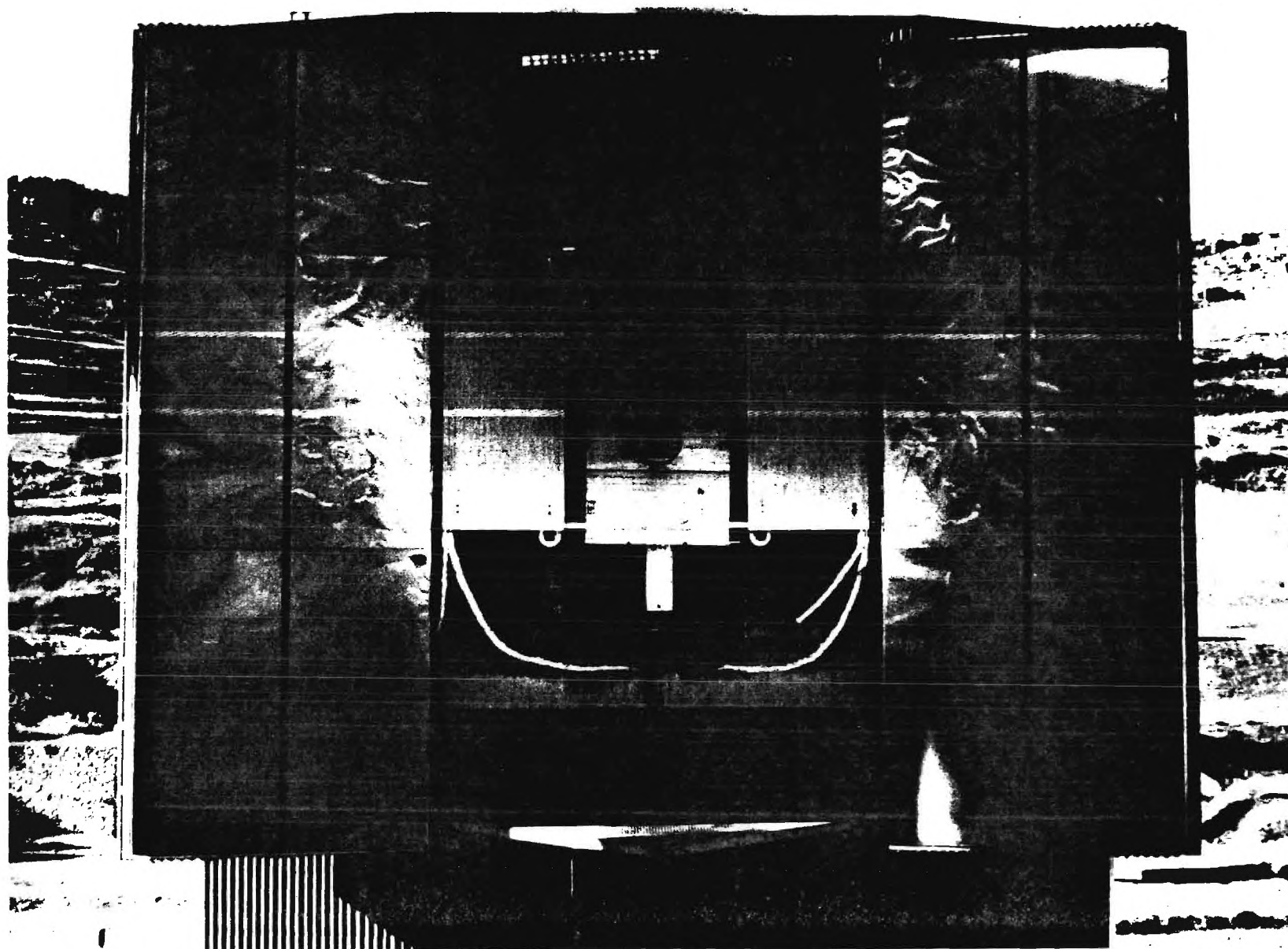


Figure 4. SAI light pipe assembly in focal room of CNRS 1000 kW Solar Furnace.

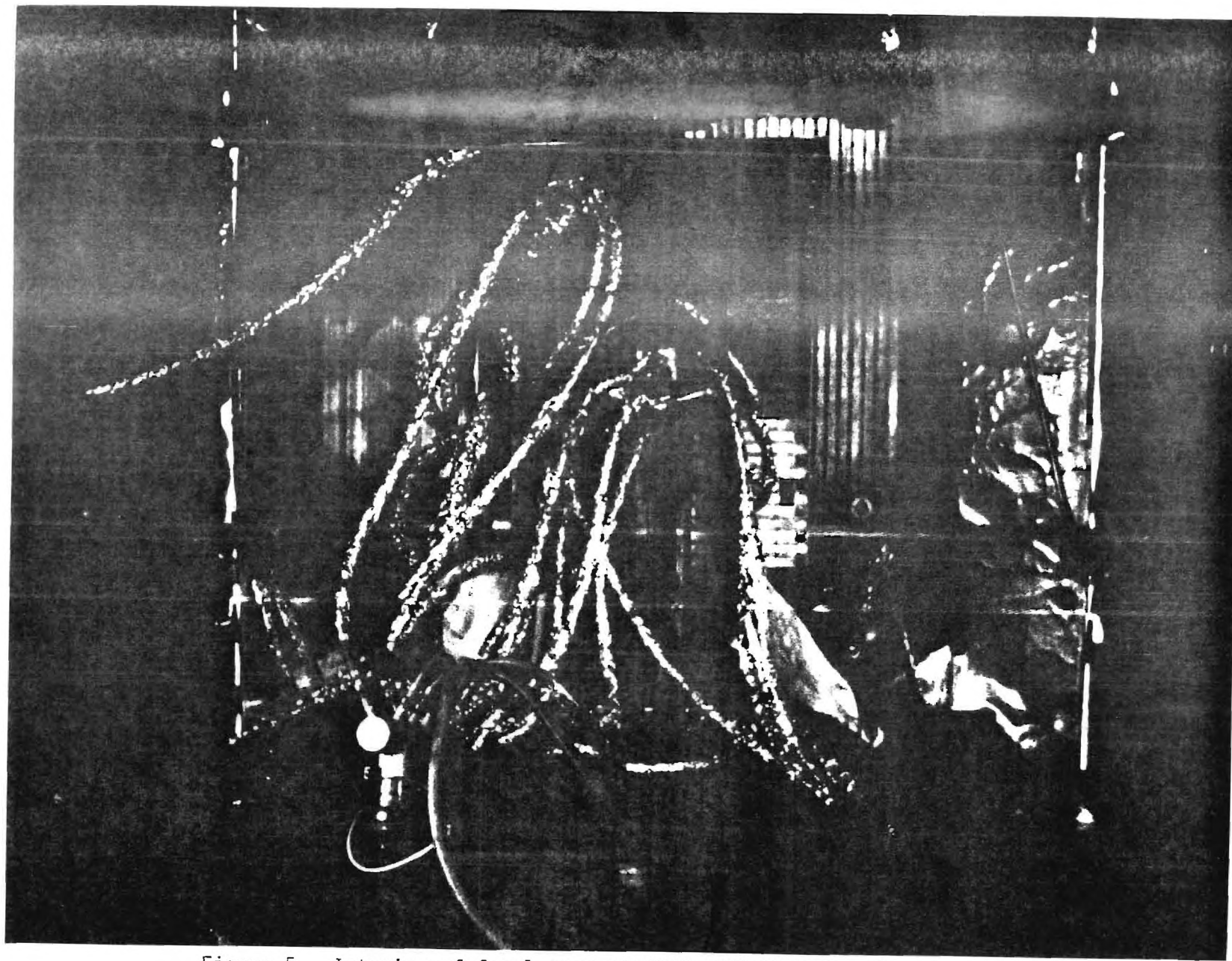


Figure 5. Interior of focal room of CNRS 1000 kW Solar Furnace during August 1979 test program.

- (3) To check the survivability of thin shutter materials which were to be used without cooling for pulse-shaping shutters.
- (4) To run several soil samples for qualitative inspection of their responses to high-intensity radiant energy, their tendency to deposit dust on the chamber walls, and any unexpected behavior.
- (5) To make trial exposures of movie films.

Approximately 70 runs were made during this test period, about 42 for calorimetry at various locations, 11 for evaluating shutter materials, five for soil tests, and 12 by CNRS for calorimetry.

The calorimetry measurements were in rather good agreement with similar measurements made at the ACTF, considering the difference in characteristics of the two facilities; flux throughput was found to be about 33 percent (versus 25 at the ACTF) and flux uniformity was found to be within about 10 percent of the average (the same value measured at the ACTF).

The cooling system worked satisfactorily except for failure of a water cooled shield which matched the square inlet aperture of the diverter to a circular aperture in the CNRS shields. Boiling was heard in some areas of the equipment, but this was controlled by increasing cooling water flow rates and rearranging hose connections to minimize the formation of air pockets.

Of the shutter materials, specular silver plating on copper and brass substrates and polished silver alone withstood five to ten seconds of exposure at the diverter outlet plane. Aluminum, nickel, diffuse silver plated on brass, stainless steel, and combinations of silver and nickel platings failed in two to six seconds. The shutter material tests indicated that none of the thin, uncooled materials could be expected to withstand the flux at the diverter exit for more than about ten seconds; synchronizing of the water-cooled shutters and the pulse-shaping shutters would thus be a critical requirement.

The five soil tests were made on separate samples obtained from the lawn near the CNRS focal building. Fusing of particles, darkening, and ejection of material was observed on vegetation-free soils. The vegetation on one soil burned immediately upon exposure and filled the sample chamber with smoke, thereby protecting the soil surface from fusing and charring. Color movies were made on four of the soils; the first run was used for exposure measurement. There was a pronounced tendency for dirt particles to collect on the sample chamber walls during the soil runs, necessitating cleaning after each run to prevent deterioration of the flux level at the soil plane.

The following system modifications were identified for future tests:

- (1) Larger window areas were required in the sample chamber to allow most of the soil surface to be observed by cameras; this was a high-priority item because of the importance of the movie data.
- (2) A hinged panel was needed on the sample chamber to permit cleaning of the walls after each run.
- (3) A system for heating the circulating water was needed to prevent condensation of atmospheric moisture on the sample chamber walls and the cooling system piping should be arranged to avoid air pockets.

- (4) Several movie cameras were needed to obtain adequate documentation from different perspectives.
- (5) A stiffer frame was needed to support the apparatus rigidly.

TEST PROGRAM AT THE CNRS SOLAR FURNACE, FEBRUARY 1980

The first test program whose objective was to acquire soil response data in a systematic manner was conducted at the CNRS 1000 kW Solar Furnace during the period February 18 through March 7, 1980. This program included the acquisition of extensive photographic data, the use of a large number of diagnostic techniques by SAI, and a light transmission experiment conducted by the University of Denver Research Institute (DRI).

It was determined at a meeting of DNA and its contractors in January 1980 that the primary documentary movies should be made on Eastman Kodak Linagraph Shellburst 2476 film at 200 frames per second. This is a black and white film with very wide exposure latitude, developed for photographing events which have wide variations in brightness. It was planned that densitometry scales would be spliced onto each roll prior to processing, so that quantitative measurements of brightness could be made. It was also decided that a red filter would be used in order to minimize the recording of scattered light. DRI was in possession of suitable movie cameras owned by DNA, and furnished four D. B. Milliken 4CD cameras for the test program. These are electrically-driven, pin-registered, 16 mm cameras, capable of framing rates up to 500 images per second.

Tests of the camera, film, filter and processing combinations began at GIT on February 1, 1980. Three Kodak Wratten filters were tested, #25 with a short wavelength cutoff at 5900 Angstroms, #70 with a short wavelength cutoff at 6500 Angstroms, and #92 with a short wavelength cutoff at 6200 Angstroms. Using a Kodak Versamat film processor, speeds of 2, 3, 4, and 6 feet per minute were used to process the film. Light meter readings were taken on a Kodak 18 percent neutral gray test card prior to exposing each test film using an assumed ASA setting of 250, and two different graded gray scales and a color control card were photographed. The resulting test negatives were used to evaluate the processing, determine if an equivalent ASA speed of 250 was appropriate, and select an exposure factor to compensate for the red filter. At a processing speed of 4 feet per minute, satisfactory agreement between the light meter readings at ASA 250 and the negative densities was found. It was then determined that a filter correction of four stops was needed for the #70 Wratten filter.

Two GIT engineers arrived at the CNRS Solar Furnace in February and participated with SAI personnel in setting up apparatus in the focal room, including equipment assembly, documentation of equipment positions (for future geometric analyses), and hookup to the 60-Hertz power system provided by GIT. A description of the movie camera arrangement is shown in Table 3 and a photograph of the interior of the focal room is shown in Figure 6.

Testing began on February 18 with characterization of the light pipe, radiation flux calibrations, and trial light meter readings on samples of sand. There followed seven days without sun, during which camera exposure discrepancies were recognized and plans made for resolution. When testing resumed on February 26, trial exposures were made using a fourth DBM camera and the films were processed on-site. Beginning with Test No. 35 on February 27, the camera settings shown in Table 3 were adopted.

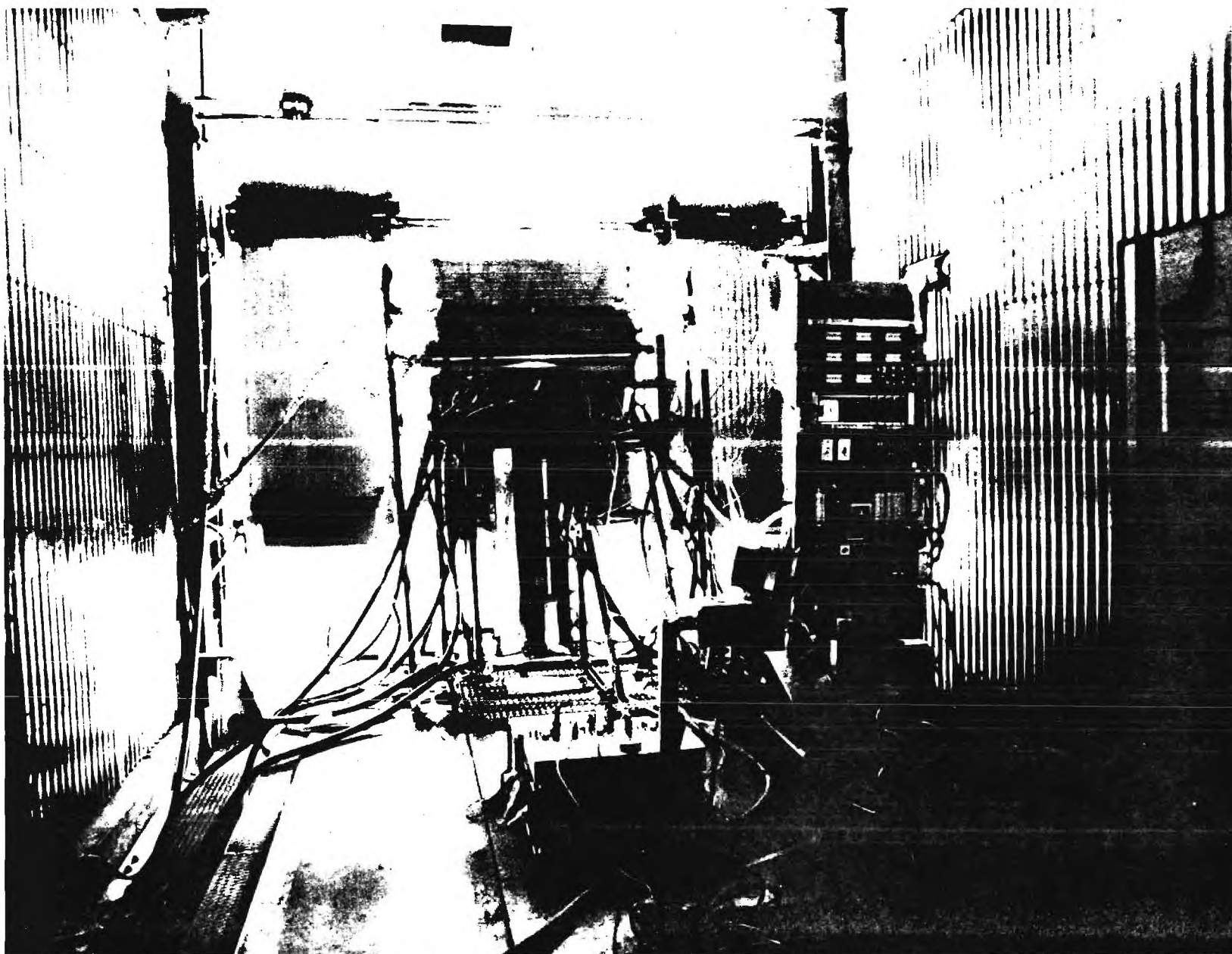


Figure 6. Interior of focal room of CNRS 1000 kW Solar Furnace during February-March 1980 test program.

Table 3. Movie camera arrangement, February-March 1980

Camera	Settings	View and rationale
DBM No. 1	f:22 1/3000 s #70	Downward view of sample surface, because cameras pointed horizontally could not see soil surface
DBM No. 2	f:16 1/3000 s #70	Horizontal view of bottom window in sample chamber, to permit particle velocity measurements immediately above sample surface
DBM No. 3	f:16 1/3000 s #70	Horizontal view of all four windows in sample chamber, to permit particle velocity measurements along entire chamber length
Bolex H16	f:5.6 1/125 s 3.00 ND	Kodachrome 25 film, 24 frames per second, held on tripod with view similar to DBM No. 1 to document appearance of sample in color

During this test program a total of 152 runs were performed. Sixty runs were made on "parametrically chosen" soils, 56 runs were made on natural (undisturbed) soils, and five runs were made on man-made surfaces such as concrete and floor tiles; the remaining runs were for apparatus checkout and calibrations. The DBM movie cameras using Linagraph Shellburst film were operated by GIT for every test and the Bolex camera using Kodachrome 25 film was operated on most tests. Before- and after-test photographs of each test specimen were made on 35 mm color slides with a reference color chart in the picture. Brightness measurements using a Minolta 1-degree spot meter were recorded before and after exposure of each specimen.

A minimum-run contingency test plan was developed in association with SAI early in the test program. This was necessary in case the number of good test days was not sufficient to allow all samples to be tested. The weekend preceding the last week of testing was devoted to adapting the light pipes and experimental set-up to accommodate the DRI transmission experiment. This required modification of the light pipe. By this time all of the undisturbed soils had been tested. Approximately 80 sample exposures had been made.

All Milliken cameras and the Bolex camera were able to continue to record the remaining 42 tests conducted during the third week. The test series consisting of the exposure of approximately 112 different soil samples was completed on Friday, March 7, 1980 at 3:11 p.m. when solar insolation decreased due to cloudy conditions.

A total of 99 rolls of Kodak Linagraph Shellburst film 2476 were hand carried back to the United States and subsequently returned to LASL for processing. This lot included 79 rolls of film from cameras 1, 2 and 3, two control rolls and 18

rolls of film exposed by DRI. Six rolls of Kodachrome movie film from the Bolex camera were also returned for processing along with 21 rolls of 35 mm film. Copies of these slides and color movie films were supplied to SAI along with a titled set of all runs including before and after slides and the movies of the tests. This color test movie is approximately 1200 feet in length. A film log indicating the approximate content of each roll of Linagraph film was also generated. This was to facilitate processing by LASL and allow the results to be cataloged.

At a program review meeting in May 1980, personnel from LASL expressed the judgment that all films from DBM Camera No. 1 were overexposed except at the initial opening of the shutters. This film was exposed with a #70 Wratten filter in the optical path, which transmits less than 0.1 percent of radiation of a wavelength less than 6415 Angstroms. The high-density image recorded by DBM Camera No. 1 may be due to black body radiation emitted by the soil as its temperature increases. This radiation is above the lower wavelength limit of the filter and below the upper wavelength sensitivity of the film (7000 Angstroms). As the soil sample heats up, the amount of black body radiation between 6415 and 7000 Angstroms will increase in proportion to the fourth power of the absolute temperature. Although the Linagraph Shellburst films were judged to be overexposed, this was preferable to underexposure because all data can be retrieved due to the four decade dynamic range of the film.

TEST PROGRAM AT THE CNRS SOLAR FURNACE, SEPTEMBER 1980

The second test program whose objective was to acquire soil response data in a systematic manner was conducted at the CNRS 1000 kW Solar Furnace during the period September 8 through 26, 1980. At a meeting of the several DNA contractors participating in this program on May 29, 1980, the following modifications of procedures used in the February-March program were defined:

- (1) The film used in the No. 1 movie camera should be changed from Linagraph Shellburst to Kodachrome 25 in order to acquire color information on all runs; the value of black and white densitometry measurements on films viewing the soils at oblique angles was deemed marginal.
- (2) The No. 2 and 3 movie cameras should be changed from 16 mm to 35 mm and the positioning of these cameras should be rearranged in order to increase the image sizes used for densitometry traces.
- (3) Other changes, within SAI's sphere of responsibility, should be made in order to insure that data collected in the field were compatible with program needs; specifically, direct measurement of dust and air temperature, collection of dust particles, pulse shaping, and the use of a Knollenburg probe to sample dust particle sizes were identified as being important.

LASL was able to supply three 35 mm Mitchell movie cameras with film magazines, motor drives, and suitable lenses and DRI supplied one 16 mm DBM camera which had been used in the February-March test program. The required mounting apparatus was assembled at Georgia Tech and trial films were exposed and processed. GIT purchased the necessary film supply, based on the filming time experienced in the February-March test program, and shipped the equipment and film to the CNRS facility.

GIT personnel arrived at the CNRS Solar Furnace on September 5 and participated with SAI personnel in setting up the experiment. The arrangement of the cameras is described in Table 4 and a photograph of the interior of the focal room is shown in Figure 7.

Table 4. Movie camera arrangement, September 1980

Camera	Settings	View
DBM No. 1	fill 1/2880 s 1.00 ND	Downward view of sample surface through lowest window, Kodachrome 25 film, 100 frames/s
Mitchell No. 2	f:16 1/2400 s #70	Horizontal view of two lower sample chamber windows, Linagraph Shellburst film, 100 frames/s
Mitchell No. 3	f:16 1/2400 s #70	Horizontal view of two upper sample chamber windows, Linagraph Shellburst film, 100 frames/s

During this test period a total of 276 runs were performed, of which 238 were with soil or other test surfaces and 38 were for equipment checks or calibration. Because the test runs were being made more rapidly than expected, one of the Mitchell movie cameras was abandoned about September 18 to conserve film. The supply of Linagraph Shellburst film was finally exhausted on September 24, although runs were continued until midafternoon on September 25. All runs were photographed using the DBM movie camera with Kodachrome 25 film and before- and after-test slides were made on each specimen as had been done in February-March. Brightness measurements were recorded before and after exposure of each specimen.

The following collection of photographic film was returned to the U. S. for processing and analysis:

- 53 rolls, Kodachrome 25, 35 mm, 36 exposures
- 2 rolls, Ektachrome 160, 35 mm, 36 exposures
- 5 rolls, Ektachrome 400, 35 mm, 36 exposures
- 25 rolls, Kodachrome 25, 16 mm movie, 100 feet
- 2 rolls, Ektachrome 160, 16 mm movie, 100 feet
- 16 rolls, Linagraph Shellburst, 35 mm movie, 500 feet

GIT had all color film processed, the color movies copied, and distributed appropriate films to SAI and DNA. The exposed black and white movie films were turned over to a DNA office in Albuquerque, New Mexico for handling. The DBM movie camera was returned to DRI and the Mitchell cameras were held at GIT pending instructions for disposition.

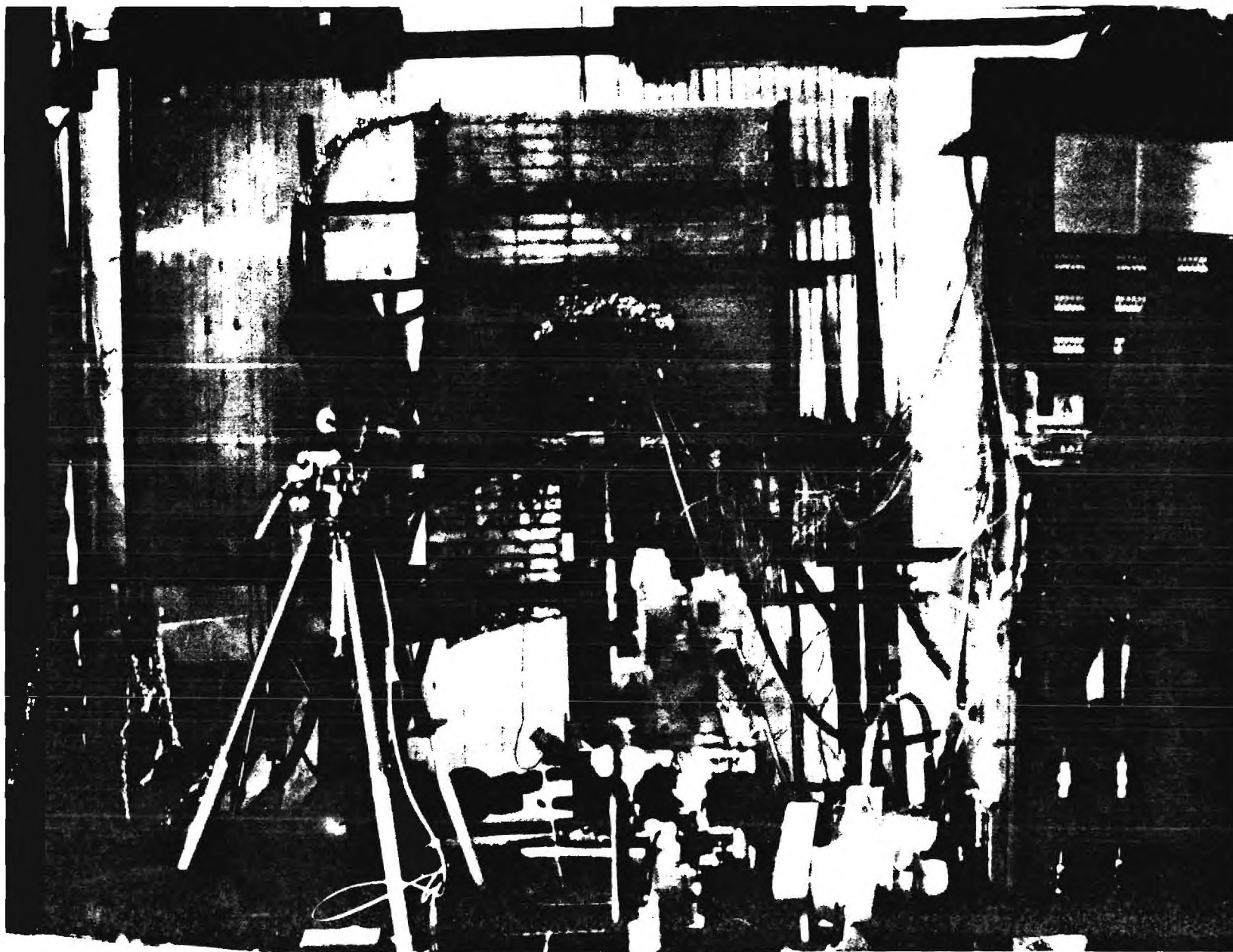


Figure 7. Interior of focal room of CNRS 1000 kW Solar Furnace during September 1980 test program.

A program review meeting was conducted on October 24 to critique the test program. At this time, there appeared to be a consensus among DNA's program contractors that data reduction should be carried out on at least one soil before additional test programs are attempted at the CNRS Solar Furnace.

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been reached on this research program:

- (1) The basic concept of the SAI designed and constructed light pipe was adequate to permit tests of soils exposed to simulated thermal pulses from nuclear weapons. The construction and the diagnostic instrumentation were not well executed, however, and serious equipment failures were experienced on each test program. For example, no soil tests with shaped pulses were ever completed during a total of 498 runs conducted at the CNRS 1000 kW Solar Furnace.
- (2) Photographic techniques appear to have been refined to the stage that adequate documentary movies can be made. Color movies are correctly exposed but further adjustment of exposure on black and white films may be required to facilitate processing by scanning densitometers. Compromises with respect to filtering may be required to overcome the tendency of emitted radiation to increase film exposure levels.
- (3) A large body of experimental data on many soils and other surfaces has been acquired. Most of this information has not yet received adequate analysis. The analysis appears to be a very formidable task, but should be completed for at least a few soils before further measurement programs are undertaken.

The following recommendations with respect to future work are offered:

- (1) Since analysis of the experimental data has not been completed, it is not yet clear whether the soil measurements are suitable to meet DNA's program needs. It is recommended that the entire matrix of experimental data for one soil be assembled and inspected for usefulness. The data considered should include movies, information of temperatures, particulate material collected, weight losses, soil composition, changes in brightness and visual appearance, and anything else available. The collection should then be reviewed by manual techniques to identify those conclusions which might be obtained, such as temperatures and dust loadings as functions of time, particle velocities, redundant determinations from separate runs, etc. If it appears that detailed analysis is warranted, the collection should be processed to extract correlations meeting the DNA's needs, for the single soil selected. The feasibility of processing data from other soils can then be established from the patterns identified under this limited study.
- (2) If additional soil measurement programs are undertaken in the future, these should emphasize the acquisition of high quality physical data rather than the survey of large numbers of soils. The rule should be that all diagnostic instrumentation and measurement apparatus will be functioning correctly and calibrated before a run is made. If a piece of diagnostic data, such as a thermocouple output, has so little value that calibration is not worthwhile, then the instrument should be removed in order to simplify the experiment; conversely, if data are worth

measuring, they are worth measuring correctly. The practice of abandoning instruments when they fail, but continuing to expend solar furnace time and personnel effort to run more specimens, can no longer be justified with the contention that many soils need to be surveyed.

Q. 12.